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Bibliography for Verification and Validation in Computational Simulation

William L. Oberkampf

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Bibliography for Verification and Validation in Computational Simulation

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Abstract

A bibliography has been compiled dealing with the verification and validation of computational simulations. The references listed in this bibliography are concentrated in the field of computational fluid dynamics (CFD). However, references from the following fields are also included: operations research, heat transfer, solid dynamics, software quality assurance, software accreditation, military systems, and nuclear reactor safety. This bibliography, containing 221 references, is not meant to be comprehensive. It was compiled during the last ten years in response to the author's interest and research in the methodology for verification and validation. The emphasis in the bibliography is in the following areas: philosophy of science underpinnings, development of terminology and methodology, high accuracy solutions for CFD verification, experimental datasets for CFD validation, and the statistical quantification of model validation. This bibliography should provide a starting point for individual researchers in many fields of computational simulation in science and engineering.

Acknowledgements

The author thanks Frederick Blottner, Patrick Roache, Tim Trucano, and Daniel Aeschliman for suggestions in the accumulation of this bibliography. My thanks to Maricela Sandoval for entering the information into the bibliographic database. I also appreciate the comments and suggestions provided by Mary McWherter-Payne and Kambiz Salari of Sandia National Laboratories as reviewers for this report. This work was performed at Sandia National Laboratories, which is operated by Lockheed Martin Corp. for the U. S. Department of Energy under contract No. DE-AC04-94AL85000.

Contents

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Description of Bibliography

A bibliography has been compiled that deals with the verification and validation of computational simulations. Before describing the bibliography, the present use of the terms *verification* and *validation* should be explained. The most widely used definitions for these terms have been given by two influential organizations: the Defense Modeling and Simulation Organization (DMSO) of the Department of Defense (DoD), and the Institute of Electrical and Electronics Engineers (IEEE). The definitions given by each of these organizations are substantially different. The DMSO definitions are [DoD, 1994]:

> *Verification*: The process of determining that a model implementation accurately represents the developer's conceptual description and specifications.
>
> *Validation*: The process of determining the degree to which a model is an accurate representation of the real-world from the perspective of the intended uses of the model.

The IEEE definitions are [IEEE, 1991]:

> *Verification*: The process of evaluating a system or component to determine whether the products of a given development phase satisfy the conditions imposed at the start of that phase.
>
> *Validation*: The process of evaluating a system or component during or at the end of the development process to determine whether it satisfies specified requirements.

Essentially all of the references in this bibliography that deal with computational simulations in science and engineering and operations research use the DMSO definitions. Essentially all of the references that deal with software engineering or software quality assurance use the IEEE definitions. Be aware of the differences in meaning of the terms in the various references given in this bibliography.

The references listed in this bibliography are concentrated in the field of computational fluid dynamics (CFD). However, references from the following fields are also included: operations research, heat transfer, solid dynamics, software quality assurance, software accreditation, military systems, and nuclear reactor safety. This bibliography, containing 221 references, is not meant to be comprehensive. It was compiled during the last ten years in response to the author's interest and research in the methodology for verification and validation. The emphasis in the bibliography is in the following areas: philosophy of science underpinnings, development of terminology and methodology, high accuracy solutions for CFD verification, experimental datasets for CFD validation, and the statistical quantification of model validation. This bibliography should provide a starting point for individual researchers in many fields of computational simulation in science and engineering.

Each reference in the bibliography uses a similar format, but there is some variation due to the different types of references included. Most of the references have the following fields:

Reference Type: Either journal article, book, book section, edited book, magazine article, conference proceedings, personal communication, or report.

Author or Editor: Most references have personal authors, but some have organizational authors.

Year: Year of publication.

Title: Title of the reference.

Journal, Publisher, or Conference Name: Journal name, publisher, or title of the conference.

Date: Date of publication, presentation, or conference.

Volume or Report Number: Volume number, conference paper number, or report number.

Abstract: Abstract, abbreviated table of contents, or introductory paragraph from the reference.

Notes: The present author's informal annotated comments on the reference.

The references are listed in alphabetical order according to the first author. If multiple references have exactly the same author(s), the references are listed chronologically. To aid in finding references by date, an Index is also included. The Index gives all of the references in chronological order. However, the reference in the Index only includes the year and the author's name(s). To find complete information on the reference, one would need to look in the alphabetical listing of the references.

Alphabetical Listing of References by Author

Reference Type: Report
Author: Aeschliman, D. P.; Oberkampf, W. L.
Year: 1997
Title: Experimental Methodology for Computational Fluid Dynamics Code Validation
Institution: Sandia National Labs.
Date: Sept. 1997
Report Number: SAND95-1189
Abstract: Validation of Computational Fluid Dynamics (CFD) codes is an essential element of the code development process. Typically, CFD code validation is accomplished through comparison of computed results to previously published experimental data that were obtained for some other purpose, unrelated to code validation. As a result, it is a near certainty that not all of the information required by the code, particularly the boundary conditions, will be available. The common approach is therefore unsatisfactory, and a different method is required. This paper describes a methodology developed specifically for experimental validation of CFD codes. The methodology requires teamwork and cooperation between code developers and experimentalists throughout the validation process, and takes advantage of certain synergisms between CFD and experiment. The methodology employs a novel uncertainty analysis technique which helps to define the experimental plan for code validation wind tunnel experiments, and to distinguish between and quantify various types of experimental error. The methodology is demonstrated with an example of surface pressure measurements over a model of varying geometrical complexity in laminar, hypersonic, near perfect gas, 3-dimensional flow.
Notes: Presents methodology for the design and execution of CFD validation experiments.

Reference Type: Journal Article
Author: Aeschliman, Daniel P.; Oberkampf, William L.
Year: 1998
Title: Experimental Methodology for Computational Fluid Dynamics Code Validation
Journal: AIAA Journal
Volume: 36
Issue: 5
Pages: 733-741
Abstract: Validation of computational fluid dynamics (CFD) codes is an essential element of the code development process. Typically, CFD code validation is accomplished through comparison of computed results to previously published experimental data that were obtained for some other purpose, unrelated to code validation. As a result, it is a near certainty that not all of the information required by the code, particularly the boundary conditions, will be available. The common approach is, therefore, unsatisfactory, and a different method is required. A methodology is described that was developed specifically for experimental validation of CFD codes. The methodology requires teamwork and cooperation between code developers and experimentalists throughout the validation process and takes advantage of certain synergisms between CFD and experiment. The methodology employs a novel uncertainty analysis technique, which helps to define the experimental plan for code validation

wind-tunnel experiments and to distinguish between and quantify various types of experimental error. The methodology is demonstrated with an example of surface pressure measurements over a model of varying geometrical complexity in laminar, hypersonic, near perfect gas, three-dimensional flow.
Notes: Presents methodology for the design and execution of CFD validation experiments.

Reference Type: Report
Author: AGARD
Year: 1979
Title: Experimental Data Base for Computer Program Assessment
Institution: NATO Advisory Group for Aerospace Research & Development
Date: May 1979
Report Number: AGARD-AR-138
Abstract: To aid in the development and refinement of computational methods and to improve their applicability and compatibility, an Experimental Data Base was established, presenting selected test results and detailed geometric descriptions of representative airfoil, wing, wing-body and body-alone configurations. In addition, the basic limitations of the available data as well as suggestions for future tests designed to reduce these limitations are discussed in detail.
Notes: Very good experimental database for CFD validation.

Reference Type: Report
Author: AGARD
Year: 1984
Title: Experimental Data Base for Computer Program Assessment: Addendum
Institution: NATO Advisory Group for Aerospace Research & Development
Date: July 1984
Report Number: AGARD-AR-138-ADDENDUM
Notes: Very good experimental database for CFD validation.

Reference Type: Report
Author: AGARD
Year: 1994
Title: A Selection of Experimental Test Cases for the Validation of CFD Codes
Institution: NATO Advisory Group for Aerospace Research & Development
Date: Aug. 1994
Report Number: AGARD-AR-303-Vol. I
Abstract: Section 1 Introduction
Section 2 CFD requirements for code validation
Section 3 Requirements for experiments for CFD validation
Section 4 Introduction to the data
Section 5 Summary of selected test cases
Section 6 Overall assessment of test cases and recommendations for the future
Notes: Very good experimental database for CFD validation.

Reference Type: Report
Author: AGARD
Year: 1994
Title: A Selection of Experimental Test Cases for the Validation of CFD Codes
Institution: NATO Advisory Group for Aerospace Research & Development
Date: Aug. 1994
Report Number: AGARD-AR-303-Vol. II
Abstract: In 1979 AGARD's Fluid Dynamics Panel established Working Group 4 to compile a number of suitable experiments for such a comparison. This has resulted in AGARD AR-138 (together with an Appendix published in 1984). The working group limited its scope at that time to two-dimensional airfoils, slender bodies and wing/body configurations. Some of the test cases have been used extensively in the past and are still used today. Since the publication of AR-138, CFD methods have improved considerably. More complex geometrical configurations with much more complex flow fields can now be calculated in fine detail. As a result of this, detailed experiments that cover a wider range of flow types and geometries are required for CFD validation. Many experiments that suit these needs have been made, but the results are not always easily accessible. For that reason AGARD FDP decided in 1990 to establish another Working Group on "The Selection of Experimental Test Cases for CFD Validation". The first meeting of the Working Group took place in Amsterdam in the fall of 1990 and 7 meetings later the working group members returned to Amsterdam for their final meeting.
Notes: Very good experimental database for CFD validation.

Reference Type: Report
Author: AIAA
Year: 1995
Title: Assessment of Wind Tunnel Data Uncertainty
Institution: American Institute of Aeronautics and Astronautics
Date: 1995
Report Number: S-071-1995
Abstract: This AIAA Standard provides a new methodology for assessment of measurement uncertainties and a technique for evaluating wind tunnel error sources. The methodology is then applied to a force and pressure test. The document is based on a Report of the NATO Advisory Group on Aerospace Research and Development (AGARD).
Notes: Good for methodology of assessing uncertainty for validation data

Reference Type: Report
Author: AIAA
Year: 1998
Title: Guide for the Verification and Validation of Computational Fluid Dynamics Simulations
Institution: American Institute of Aeronautics and Astronautics
Date: June 1998
Report Number: AIAA-G-077-1998
Abstract: The document presents guidelines for assessing the credibility of modeling and simulation in computational fluid dynamics. The two main principles that are necessary for

credibility are verification and validation. Verification is the process of determining if a computational simulation accurately represents the conceptual model, but no claim is made of the relationship of the simulation to the real world. Validation is the process of determining if a computational simulation represents the real world. This document defines a number of key terms, discusses fundamental concepts, and specifies general procedures for conducting verification and validation of computational fluid dynamics simulations. The document's goal is to provide a foundation for the major issues and concepts in verification and validation. However, this document does not recommend standards in these areas because a number of important issues are not yet resolved. It is hoped that the guidelines will aid in the research, development, and use of computational fluid dynamics simulations by establishing common terminology and methodology for verification and validation. The terminology and methodology should also be useful in other engineering and science disciplines.
Notes: First engineering society guide for V&V standards

Reference Type: Edited Book
Editor: Andriole, Stephen J.
Year: 1986
Title: Software Validation Verification Testing and Documentation
Publisher: Petrocelli Books
City: Princeton, New Jersey
Edition: 1st
Abstract: Book One: Planning for Software Validation, Verification, and Testing
Book Two: Validation, Verification and Testing of Computer Software
Book Three: Software Testing
Book Four: Software Validation, Verification and Testing Technique and Tool Reference Guide
Book Five: Management Guide to Software Documentation
Book Six: Computer Model Documentation Guides
Notes: Fairly good from the software quality perspective. Uses IEEE definitions for V & V in modeling and simulation. Book is somewhat dated.

Reference Type: Report
Author: anonymous
Year: 1995
Title: An Accreditation Support Framework for DoD Models and Simulations
Institution: JTCG/AS
Date: January 1995
Report Number: JTCG/AS-95-M-004
Abstract: This document describes an incremental model and simulation (M&S) accreditation support process developed under the auspices of the Susceptibility Model Assessment and Range Test (SMART) Project. The SMART Project was commissioned by the Office of the Secretary of Defense (OSD) in FY92 to: (1) develop a process for improving the credibility of M&S used to support acquisition decisions for airborne weapon systems; (2) test the proposed process on a set of existing M&S widely used in the Department of Defense (DoD); and (3) transition the process and support infrastructure to DoD organizations for expansion of the

methodology to other types of M&S. The accreditation support process developed to fulfill these objectives includes verification, validation and configuration management (VV&CM) activities, and it is divided into three sequential phases, each of which produces a set of accreditation support products at successively greater levels of detail. These products (called Accreditation Support Packages, or ASP's) provide a standard way to report VV&CM results, and they summarize the essential information required to make accreditation decisions as defined by a survey of M&S users and policy makers who are actually involved in making those decisions. The three phases of VV&CM activity that comprise the accreditation support process are: Phase I - Model Characterization, Phase II - Expert Review, and Phase III - Detailed Verification and Validation.
Notes: Does not define what verification, validation, and accreditation mean.

Reference Type: Report
Author: ANS
Year: 1987
Title: American Nuclear Society: Guidelines for the Verification and Validation of Scientific and Engineering Computer Programs for the Nuclear Industry
Date: 1987
Report Number: ANSI/ANS-10.4-1987
Abstract: The purpose of this standard is to provide guidelines for the verification and validation of scientific and engineering computer programs developed for nuclear industry applications. The standard does not recommend a specific approach to program development, but does recommend that verification and validation activities be carried out in parallel with program development. For a specific project, the project sponsor should determine the level of the verification and validation effort to be applied. The standard complements the following ANS-10 standards relating to computer program development:
American National Standard Guidelines for the Documentation of Digital Computer Programs, ANSI/ANS-10.3-1986.
American National Standard Guidelines for Considering User Needs in Computer Program Development, ANSI/ANS-10.5-1986.
American National Standard for Recommended Programming Practices to Facilitate the Portability of Scientific Computer Programs, ANSI/ANS-10.2-1982.
In addition, an effort has been made to maintain consistency in terminology and concepts with various software standards being developed under the sponsorship of the Institute of Electrical and Electronics Engineering, Inc. (IEEE) and to identify areas of disagreement.
Notes: Uses IEEE definitions of verification and validation.

Reference Type: Conference Proceedings
Author: Arthur, James D.; Nance, Richard E.
Year: 1996
Title: Independent Verification and Validation: A Missing Link in Simulation Methodology?
Conference Name: 1996 Winter Simulation Conference
Editor: Charnes, John M.; Morrice, Douglas J.; Brunner, Daniel T.; Swain, James J.
Conference Location: Coronado, CA
Pages: 229-236
Abstract: Independent verification and validation (IV&V) is a powerful tool that can be used to

mitigate the increasing complexities associated with an ever-expanding set of modeling and simulation problems. In this paper we discuss the use of independent V&V within the modeling and simulation community. Literature reviews and conversations with experienced technical managers serve as a basis for our conjecture that (a) validation is the major focus of most modeling and simulation efforts, (b) verification plays only a secondary role, and (c) independent V&V is, for all practical purposes, being ignored. In an effort to raise the awareness of the benefits and applicability of independent V&V within the modeling and simulation community, we describe in a step-by-step fashion the application of independent V&V to one particular life cycle model of a simulation model.
Notes: Authors give a very good review of verification and validation procedures and the value of independent V&V.

Reference Type: Book
Author: Baber, R.
Year: 1987
Title: The Spine of Software; Designing Provably Correct Software: Theory and Practice
Publisher: Wiley
City: New York
Notes: Very good modern reference for verification

Reference Type: Conference Proceedings
Author: Bailey, Michael P.; Kemple, William G.
Year: 1992
Title: The Scientific Method of Choosing Model Fidelity
Conference Name: 1992 Winter Simulation Conference Proceedings
Editor: Swain, James J.; Goldsman, David; Crain, Robert C.; Wilson, James R.
Conference Location: Arlington, VA
Pages: 790-797
Abstract: Simulation modeling currently enjoys great popularity as a tool for solving problems within Department of Defense activities. In this work we consider the process of upgrading an existing simulation model by increasing the fidelity of the model. The submodels to be upgraded and the degree to which they are upgraded should be chosen in a coherent, scientific manner. This is currently not the norm.
In this work we describe a method which a simulation analyst can use to choose from a set of proposed model upgrades that accounts for both the costs of the upgrade as well as the benefits.
Notes: Has a good discussion of conceptual model formulation and validation

Reference Type: Journal Article
Author: Balachandar, S.; Mittal, R.; Najjar, F. M.
Year: 1997
Title: Properties of the Mean Recirculation Region in the Wakes of Two-Dimensional Bluff Bodies
Journal: Journal of Fluid Mechanics
Volume: 351

Pages: 167-199
Abstract: The properties of the time- and span-averaged mean wake recirculation region are investigated in separated flows over several different two-dimensional bluff bodies. Ten different cases are considered and they divide into two groups: cylindrical geometries of circular, elliptic and square cross-sections and the normal plate. A wide Reynolds number range from 250 to 140000 is considered, but in all the cases the attached portion of the boundary layer remains laminar until separation. The lower Reynolds number data are from direct numerical simulations, while the data at the higher Reynolds number are obtained from large-eddy simulation and the experimental work of Cantwell & Coles (1983), Krothapalli (1996, personal communication), Leder (1991) and Lyn et al (1995). Unlike supersonic and subsonic separations with a splitter plate in the wake, in all the cases considered here there is strong interaction between the shear layers resulting in Karman vortex shedding. The impact of this fundamental difference on the distribution of Reynolds stress components and pressure in relation to the mean wake recirculation region (wake bubble) is considered. It is observed that in all cases the contribution from Reynolds normal stress to the force balance of the wake bubble is significant. In fact, in the cylinder geometries this contribution can outweigh the net force from the shear stress, so that the net pressure force tends to push the bubble away from the body. In contrast, in the case of normal plate, owing to the longer wake, the net contribution from shear stress outweighs that from the normal stress. At higher Reynolds numbers, separation of the Reynolds stress components into incoherent contributions provides more insight. The behavior of the coherent contribution, arising from the dominant vortex shedding, is similar to that at lower Reynolds numbers. The incoherent contribution to Reynolds stress, arising from small-scale activity, is compared with that of a canonical free shear layer. Based on these observations a simple extension of the wake model is proposed.
Notes: Good paper for CFD verification.

Reference Type: Conference Proceedings
Author: Balci, Osman
Year: 1994
Title: Validation, Verification, and Testing Techniques throughout the Life Cycle of a Simulation Study
Conference Name: 1994 Winter Simulation Conference
Conference Location: Lake Buena Vista, Florida
Pages: 215-220
Abstract: Life cycle validation, verification, and testing (VV&T) is extremely important for the success of a simulation study. This paper surveys current software VV&T techniques and current simulation model VV&T techniques and describes how they can all be applied throughout the life cycle of a simulation study. The processes and credibility assessment stages of the life cycle are described and the applicability of the VV&T techniques for each stage is stated.
Notes: Some of the ideas in the paper are interesting, but some of his definitions are confusing.

Reference Type: Journal Article
Author: Balci, Osman; Nance, Richard E.
Year: 1985

B

Title: Formulated Problem Verification as an Explicit Requirement of Model Credibility
Journal: Simulation
Volume: 45
Issue: 2
Pages: 76-86
Abstract: This paper deals with the formulation and formulation verification of a class of problems to which "modeling solutions" are applied. Two main objectives are to develop a procedure for problem formulation and to propose indicators for the formulated problem verification. The class of problems considered is analyzed in two categories as requiring prescriptive or descriptive solutions. A detailed study of each category results in a procedure to guide the analyst during the problem formulation. This procedure is illustrated by a traffic intersection problem. The formulated problem is measured by using indicators to accomplish an evaluation for the formulated verification. Indicators are developed to measure (1) the probability of failing to solve the actual problem, (2) the acceptability of an alternative set of possible outcomes, and (3) how well the formulated problem is structured. An evaluation questionnaire, included in the Appendix, is employed in applying the proposed indicators.
Notes: Has a good description of the steps and possible errors in model formulation, i.e., conceptual modeling phase

Reference Type: Journal Article
Author: Balci, Osman; Sargent, Robert G.
Year: 1984
Title: A Bibliography on the Credibility Assessment and Validation of Simulation and Mathematical Models
Journal: Simuletter
Volume: 15
Issue: 3
Pages: 15-27
Abstract: A review of the published literature indicates that a uniform, standard terminology is yet nonexistent. Several terms are used. Sometimes, a term used by a modeler in one area has a different meaning when used by a modeler in another area. Commonly encountered language includes the following 16 terms: acceptability, accuracy, analysis, assessment, calibration, certification, confidence, credibility, evaluation, performance, qualification, quality assurance, reliability, testing, validation, and verification.
Notes: The best literature review on verification and validation that I have seen. They give 308 references to V&V literature before 1984.

Reference Type: Book
Author: Banks, Jerry; Carson, John S., II
Year: 1984
Title: Discrete-Event System Simulation
Publisher: Prentice-Hall, Inc.
City: Englewood Cliffs, New Jersey
Edition: 1st
Abstract: Part One: Introduction to Discrete-Event System Simulation

Part Two: Mathematical and Statistical Models
Part Three: Random Numbers
Part Four: Analysis of Simulation Data
From Chapter 1:
A simulation is the imitation of the operation of a real-world process or system over time. Whether done by hand or on a computer, simulation involves the generation of an artificial history of a system, and the observation of that artificial history to draw inferences concerning the operating characteristics of the real system.
From Chapter 10:
One of the most important and difficult tasks facing a model developer is the verification and validation of the simulation model. The users of a model, the engineers and analysts who use the model outputs to aid in making design recommendations, and the managers who make decisions based on these recommendations, justifiably look upon a model with some degree of skepticism about its validity. To reduce this skepticism and to increase the model's credibility, it is the job of the model developer to work closely with the end users throughout the period of development and validation. The goal of the validation process is twofold: (1) to produce a model that represents true system behavior closely enough for the model to be used as a substitute for the actual system for the purpose of experimenting with the system; (2) to increase to an acceptable level the credibility of the model that will be used by managers and other decision makers.
Notes: Chapter 10: Verification and Validation of Simulation Models

Reference Type: Conference Proceedings
Author: Barber, T. J.
Year: 1996
Title: The Role of Code Validation and Certification in the Design Environment
Conference Name: 27th AIAA Fluid Dynamics Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: New Orleans, LA
Volume: AIAA Paper No. 96-2033
Abstract: This paper considers the question frequently asked after a CFD solution has been obtained, i.e. "how do I know my answer is correct?" Most engineering organizations using CFD codes in support of their design processes attempt to assess this issue and reduce the risks incurred by evaluating the usability of the results: While there are several forms of risk, the primary issues focused on in this paper are accuracy and reduced variability (robustness). The role of benchmark or validation studies in establishing a code's accuracy is examined. Examples are presented illustrating the difficulty in relying on benchmark studies to validate a code for design usage. Ways of reducing code usage variability are also suggested, including performing numerical experiments and design calibrations.
Notes: Has one of the first graphics to show coordinates in a multidimensional space of uncertainty estimation. Good for suggesting levels of complexity in code validation.

Reference Type: Journal Article
Author: Barber, T. J.
Year: 1998

B

Title: Role of Code Validation and Certification in the Design Environment
Journal: AIAA Journal
Volume: 36
Issue: 5
Pages: 752-758
Abstract: The question frequently asked after a computational fluid dynamics (CFD) solution has been obtained, How do I know my answer is correct? is considered. Most engineering organizations using CFD codes in support of their design processes attempt to assess this issue and to reduce the risks incurred by evaluating the usability of the results. Whereas there are several forms of risk, the primary issues focused on in this work are accuracy and reduced variability (robustness). The role of benchmark or validation studies in establishing a code's accuracy is examined. Examples are presented illustrating the difficulty in relying on benchmark studies to validate a code for design usage. Ways of reducing code usage variability are also suggested, including performing numerical experiments and design calibrations.
Notes: Has one of the first graphics to show coordinates in a multidimensional space of uncertainty estimation. Good for suggesting levels of complexity in code validation.

Reference Type: Journal Article
Author: Barkley, Dwight; Henderson, Ronald D.
Year: 1996
Title: Three-Dimensional Floquet Stability Analysis of the Wake of a Circular Cylinder
Journal: Journal of Fluid Mechanics
Volume: 322
Pages: 215-241
Abstract: Results are reported from a highly accurate, global numerical stability analysis of the periodic wake of a circular cylinder for Reynolds numbers between 140 and 300. The analysis shows that the two-dimensional wake becomes (absolutely) linearly unstable to three-dimensional perturbations at a critical Reynolds number of 188.5 +/- 1.0. The critical spanwise wavelength is 3.96 +/- 0.02 diameters and the critical Floquet mode corresponds to a "Mode A' instability. At Reynolds number 259 the two-dimensional wake becomes linearly unstable to a second branch of modes with wavelength 0.822 diameters at onset. Stability spectra and corresponding neutral stability curves are presented for Reynolds numbers up to 300.
Notes: Good paper for CFD verification.

Reference Type: Journal Article
Author: Barragy, E.; Carey, G. F.
Year: 1997
Title: Stream Function-Vorticity Driven Cavity Solution Using p Finite Elements
Journal: Computers and Fluids
Volume: 26
Issue: 5
Pages: 453-468
Abstract: Calculations for the two-dimensional driven cavity incompressible flow problem are presented. A p-type finite element scheme for the fully coupled stream function-vorticity formulation of the Navier-Stokes equations is used. Graded meshes are used to resolve vortex flow features and minimize the impact of corner singularities. Incremental continuation in the

Reynolds number allows solutions to be computed for Re = 12500. A significant feature of the work is that new tertiary and quaternary corner vortex features are observed in the flow field. Comparisons are made with other solutions in the literature.
Notes: Good paper for CFD verification.

Reference Type: Journal Article
Author: Beck, M. B.
Year: 1987
Title: Water Quality Modeling: A Review of the Analysis of Uncertainty
Journal: Water Resources Research
Volume: 23
Issue: 8
Pages: 1393-1442
Abstract: This paper reviews the role of uncertainty in the identification of mathematical models of water quality and in the application of these models to problems of prediction. More specifically, four problem areas are examined in detail: uncertainty about model structure, uncertainty in the estimated model parameter values, the propagation of prediction errors, and the design of experiments in order to reduce the critical uncertainties associated with a model. The review is rather lengthy, and it has therefore been prepared in effect as two papers. There is a shorter, largely nontechnical version, which gives a quick impression of the current and future issues in the analysis of uncertainty in water quality modeling. Enclosed by this shorter discussion is the main body of the review dealing in turn with (1) identifiability and experimental design, (2) the generation of preliminary model hypotheses under conditions of sparse, grossly uncertain field data, (3) the selection and evaluation of model structure, (4) parameter estimated (model calibration), (5) checks and balances on the identified model, i.e., model "verification" and model discrimination, and (6) prediction error propagation. Much time is spent in discussing the algorithms of system identification, in particular, the methods of recursive estimation, and in relating these algorithms and the subject of identification to the problems of prediction uncertainty and first-order error analysis.
Notes: He has a very good review of fundamentals of uncertainty estimation in modeling and simulation. He formulates most of the primary questions in uncertainty estimation. He also has a very good description of validation procedures using statistical methods.

Reference Type: Book
Author: Beizer, B.
Year: 1990
Title: Software Testing Techniques
Publisher: Van Nostrand Reinhold
City: New York
Notes: Very good modern reference for verification.

Reference Type: Book Section
Author: Bell, James A.; Bell, James F.
Year: 1980
Title: System Dynamics and Scientific Method

B

Book Title: Elements of the System Dynamics Method
Editor: Randers, Jorgen
Publisher: MIT Press
Abstract: Recognition that science is not absolute truth raises a question: Then what is it? The practice of system dynamics and its alternatives is deeply affected by three views that have emerged as answers. One view maintains that scientific knowledge is a tool - an instrument - that consists of data correlations. It is advanced by correlating more and more data and/or by finding correlations with a closer statistical fit to the data. This view, instrumentalism, underlies much work in the social sciences, including econometrics. According to another view, scientific knowledge consists of groups of ideas - paradigms - that explain phenomena. It advances by forcing the ideas on data until serious misfits require adoption of another paradigm. Paradigm has intrigued numerous social scientists, including system dynamicists. The third view holds that scientific knowledge consists of conjectures that are refutations. Refutationism is the view used in good system dynamics practice. Despite its long and successful tradition in the physical sciences, it is not widely embraced by social scientists.
Notes: This is one of the best articles on the history of the scientific method. It also has some good ideas that apply to verification and validation

Reference Type: Conference Proceedings
Author: Belter, Dale L.
Year: 1998
Title: Comparison of Wind Tunnel Data Repeatability with Uncertainty Analysis Estimates
Conference Name: 20th AIAA Advanced Measurement and Ground Testing Technology Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Albuquerque, NM
Volume: AIAA 98-2714
Pages: 11
Abstract: When assessing the quality of the wind-tunnel data being acquired at the Boeing Aerodynamics Laboratory, data repeatability is a first concern. Baseline configurations from previous tests, and multiple repeats of a baseline configuration within a test are used by the customer and test personnel to obtain confidence in the test data. One piece missing from the repeatability analysis is the estimated repeatability obtainable from the current test setup. This paper explores some of the tools being used to estimate data repeatability and compares these estimates to test data.
Notes: Good for estimating experimental uncertainty in validation data

Reference Type: Conference Proceedings
Author: Benek, John A.; Kraft, Edward M.; Lauer, Rodney F.
Year: 1996
Title: Validation Issues for Engine/Airframe Integration
Conference Name: 27th AIAA Fluid Dynamics Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: New Orleans, LA
Volume: AIAA 96-2031

Pages: 9
Abstract: A review of the engine/airframe integration methodology is made and some process deficiencies are identified. The use of CFD as an alternative simulation source is discussed. An approach toward combining computations with the existing integration methodology is suggested. Validation issues associated with the computational procedures are examined. CFD as a source of test facility corrections is found to be well developed, but validation efforts remain ad hoc. The use of CFD for fighter aircraft to evaluate inlet drag increments and to generate high resolution total pressure maps is discussed. Related validation issues include the simulation of unsteady flow with steady state approximations.

Reference Type: Journal Article
Author: Benek, John A.; Kraft, Edward M.; Lauer, Rodney F.
Year: 1998
Title: Validation Issues for Engine - Airframe Integration
Journal: AIAA Journal
Volume: 36
Issue: 5
Pages: 759-764
Abstract: The engine-airframe integration methodology is reviewed and some process deficiencies are identified. The use of computational fluid dynamics as an alternative simulation source is discussed. An approach toward combining computations with the existing integration methodology is suggested. Validation issues associated with the computational procedures are examined. Computational fluid dynamics as a source of test facility corrections is found to be well developed, but validation efforts remain ad hoc. The use of computational fluid dynamics to evaluate inlet drag increments and to generate high-resolution total pressure maps is discussed. Related validation issues include the simulation of unsteady flow with steady-state approximations.

Reference Type: Edited Book
Editor: Bequet, Marc C.
Year: 1992
Title: Teleoperation: Numerical Simulation and Experimental Validation
Publisher: Kluwer Academic Publishers
Volume: 4
Abstract: Some Key Issues in Remote Handling
Teleman: A European Communities Robotics Programme for the Nuclear Industry
Practical Experience Using Teleoperated Technology: Teleoperated Devices Used in an Accelerator Complex
Artificial Realities Techniques for Teleoperation of Robotic Systems
Robot Motion Planning: A Survey
Autonomous Mobile Robots and Teleoperation
Kinematic Calibration in Remote Handling and Teleoperation Environment
Transporters for Teleoperations in JET
Nuclear Teleoperation. Particular Challenges in Decommissioning Applications
Manipulators Mascot IV Used in JET and Prospects of Enhancement

B

Position Sensing for Advanced Teleoperation in Nuclear Environment
Advanced Telerobotic Systems. Single-Master Multi-Slave Manipulator System and Cellular Robotic System
Introduction to Robotics and Computer Vision
The NET Remote Maintenance Programme

Reference Type: Conference Proceedings
Author: Bertin, J. J.; Martellucci, A.; Neumann, R. D.; Stetson, K. F.
Year: 1993
Title: Developing a Data Base for the Calibration and Validation of Hypersonic CFD Codes - Sharp Cones
Conference Name: 24th AIAA Fluid Dynamics Conf.
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Orlando, FL
Volume: AIAA Paper No. 93-3044
Abstract: While supersonic flowfields about sharp cones are relatively simple, computations of these flowfields must include models of boundary layer transition, turbulence and ablation processes. Validation requires detailed data comparisons to verify the ability to compute the critical flow physics. These processes are difficult to model numerically and measure experimentally. The present paper reviews the types of data and the quality and limitations of the measurements and it provides guidance as to how the data can be used to obtain information relating to the flow mechanisms.

Reference Type: Edited Book
Editor: Blackwell, B. F.; Armaly, B. F.
Year: 1993
Title: Computational Aspects of Heat Transfer: Benchmark Problems
Publisher: American Society of Mechanical Engineers
City: New York
Volume: ASME HTD-Vol. 258
Abstract: The K-12 Aerospace Heat Transfer Committee has recognized the need to provide benchmark problems such that an engineer becoming familiar with a heat transfer computer code will have a suite of text problems to exercise the code. The first session was presented at the ASME 1993 Winter Annual Meeting and it dealt with the two-dimensional laminar flow over a backward facing step. This session is the second in this series and has added a mixed-convection component to the problem.
Notes: Very good conference proceedings for benchmark heat transfer solutions for verification.

Reference Type: Edited Book
Editor: Blackwell, B. F.; Pepper, D. W.
Year: 1992
Title: Benchmark Problems for Heat Transfer Codes
Publisher: American Society of Mechanical Engineers
City: New York
Volume: ASME HTD-Vol. 222

Abstract: The K-12 Aerospace Heat Transfer Committee has recognized the need to define benchmark problems to validate heat transfer codes. This session is intended to be the first of several sessions in the coming years devoted to benchmarking heat transfer computer codes. These sessions are designed to help define “more realistic, and difficult problems” that both code developers and users can utilize to verify software accuracy and validity. They will also provide a public forum for quantifying the “physics” of the problems and accuracies of the codes.
All of the participants of this session were asked to solve the same problem and put their results in a common format. The problem chosen was the laminar flow over a backward facing step. The hydrodynamics portion of this problem as already received considerable attention in the literature. The contribution of this first session on benchmarks is to add a heat transfer component to the problem.
Notes: Very good conference proceedings for benchmark heat transfer solutions for verification.

Reference Type: Journal Article
Author: Blottner, Frederick G.
Year: 1990
Title: Accurate Navier-Stokes Results for the Hypersonic Flow Over a Spherical Nosetip
Journal: Journal of Spacecraft and Rockets
Volume: 27
Issue: 2
Pages: 113-122
Abstract: The unsteady, thin-layer Navier-Stokes equations for a perfect gas are solved with a linearized block, alternating direction implicit finite-difference solution procedure. Solution errors due to numerical dissipation added to the governing equations are evaluated. Errors in the numerical predictions on three-different grids are determined where Richardson extrapolation is used to estimate the exact solution. Accurate computational results are tabulated for the hypersonic laminar flow over a spherical body, which can be used as a benchmark test case. Predictions obtained from the code are in good agreement with inviscid numerical results and experimental data.
Notes: Good paper for CFD code verification.

Reference Type: Conference Proceedings
Author: Boerstoel, J. W.
Year: 1988
Title: Numerical Accuracy Assessment
Conference Name: AGARD 62nd Meeting of the Fluid Dynamics Panel Symposium on Computational Fluid Dynamics
Conference Location: Lisbon, Portugal
Pages: 19
Edition: AGARD-CP-No. 437
Abstract: The first sections are devoted to putting the topic numerical accuracy assessment within a framework. Hence, the purpose of numerical flow simulations is first formulated. This formulation concerns the classes of aeronautical configurations (boundaries), the desired

flow physics (flow equations and their properties), the classes of flow conditions on flow boundaries (boundary conditions), and the initial flow conditions. Next, accuracy and economical performance requirements are defined: the final numerical flow-simulation results of interest should have a guaranteed accuracy, and be produced for an acceptable FLOP-price. Within this context, the validation of numerical processes with respect to the well-known topics of consistency, stability, and convergence when the mesh is refined must be done by numerical experimentation because theory gives only partial answers. This requires careful design of test cases for numerical experimentation.
Finally, the results of a few recent evaluation exercises of numerical experiments with a large number of codes on a few test cases are summarized.

Reference Type: Journal Article
Author: Botta, E. F. F.; Dijkstra, D.; Veldman, A. E. P.
Year: 1972
Title: The Numerical Solution of the Navier-Stokes Equations for Laminar, Incompressible Flow Past a Parabolic Cylinder
Journal: Journal of Engineering Mathematics
Volume: 6
Issue: 1
Pages: 63-81
Abstract: The numerical method of solution of van de Vooren and Dijkstra for the semi-infinite flat plate has been extended to the case of the parabolic cylinder. Results are presented for the skin friction, the friction drag, the pressure and the pressure drag. The drag coefficients have been checked by means of an application of the momentum theorem.
Notes: Good paper for CFD verification.

Reference Type: Book
Author: Bowen, J. P.; Hinchey, M. G.
Year: 1995
Title: Applications of Formal Methods
Publisher: Prentice-Hall
City: Englewood Cliff, NJ
Notes: Good modern reference on verification and formal methods.

Reference Type: Conference Proceedings
Author: Bradley, R. G.
Year: 1988
Title: CFD Validation Philosophy
Conference Name: AGARD Symposium Validation of Computational Fluid Dynamics
Publisher: North Atlantic Treaty Organization
Conference Location: Lisbon, Portugal
Volume: AGARD-CP-437
Abstract: Computational Fluid Dynamics (CFD) is becoming an increasingly powerful tool in design and analysis of fluid dynamic and aerospace systems. Application of CFD to practical design problems requires a high level of confidence, which in turn requires focused

experimentation to verify the accuracy of CFD codes. The need for CFD validation is presented from the viewpoint of the user, and a general philosophy for validation of CFD codes is introduced, highlighting the requirements for disciplined experimentation and careful evaluation of the bounds of error in CFD solutions.
Notes: This is one of the best early references on CFD validation philosophy

Reference Type: Book
Author: Bratley, Paul; Fox, Bennett L.; Schrage, Linus E.
Year: 1987
Title: A Guide to Simulation
Publisher: Springer-Verlag
City: New York
Edition: 2nd
Abstract: Ch. 1 Introduction
Ch. 2 Variance Reduction
Ch. 3 Output Analysis
Ch. 4 Rational Choice of Input Distributions
Ch. 5 Nonuniform Random Numbers
Ch. 6 Uniform Random Numbers
Ch. 7 Simulation Programming
Ch. 8 Programming to Reduce the Variance
Notes: Very good fundamental description of modeling, simulations, and terminology of verification and validation. Emphasizes the statistical side of general simulations.

Reference Type: Conference Proceedings
Author: Bussoletti, John E.
Year: 1994
Title: CFD Calibration and Validation: The Challenges of Correlating Computational Model Results with Test Data
Conference Name: 18th AIAA Aerospace Ground Testing Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Colorado Springs, CO
Volume: AIAA-94-2542
Pages: 7
Abstract: To the extent that the validation of CFD tools is intended to enhance the use of those tools in aircraft design, it is important to examine the context in which the tools are used to better understand how to validate them. Results of a survey of users of CFD tools at a major aircraft manufacturer are reported and analyzed. The results of the survey suggest what areas to emphasize in validation. Some recent experiences in gaining an understanding of discrepancies in test data and CFD models are reviewed to illustrate the need for considering validation over a "neighborhood" in parameters such as Mach number and angle of attack. A description will be offered of a wish-list of numerical tools to characterize test data "neighborhoods" in parameters such as Mach, angle of attack and Reynolds number. These considerations result in a need for a greater emphasis on quantity of validation cases.
Notes: This paper has a very good description of how CFD is used in an engineering design

environment.

Reference Type: Report
Author: Carpraux, J. F.
Year: 1994
Title: Some Software Tools to Control the Accuracy in Scientific Computing
Institution: Institut de Recherche en Informatique et Systemes Aleatoires
Date: 1994
Report Number: Publication Interne No. 873
Abstract: A main concern of scientific computing is the validation of numerical simulations. Indeed, several factors contribute to the degradation of accuracy in the final result. This thesis deals with new tools to control the accuracy for the following eigenproblem:
We present in the first part of this thesis an expert system called SESAME, which can either select the sequence of LAPACK routines solving the given problem (P) or validate a user choice of routines. It can eventually give an estimation of the accuracy of the result. The spectral portrait of a matrix provides useful information about it. Usually, the spectral portrait is computed using a Singular Value Decomposition, but this approach is not suitable for large sparse matrices. The second part of the thesis is devoted to the computation of the spectral portrait for large sparse matrices. Krylov subspaces have an important place in sparse linear algebra, since numerous iterative methods in linear algebra dealing with large sparse matrices require these subspaces. In the third part of the thesis, we study theoretically the condition number of Krylov bases and subspaces.

Reference Type: Journal Article
Author: Carson, E. R.; Flood, R. L.
Year: 1990
Title: Model Validation: Philosophy, Methodology and Examples
Journal: Trans. of the Institute of Measurement and Control
Volume: 12
Issue: 4
Pages: 178-185
Abstract: This paper proposes an integrated framework within which philosophical and methodological issues relating to model validation should be set. The viewpoint adopted is more expansive than that of traditional scientific rationality. Rather, it is suggested that there are several ways of 'dividing up reality', each of which has an associated rationality, dependent on purpose and problem context. Modelling methodology is then considered emphasizing the role of validation 'submethodologies'. Examples are presented chosen from the domains of physiology and medicine, which illustrate some of the major issues of model validation.
Notes: Deals with the philosophy of validation of models, but is somewhat confusing. Mainly deals with medical modeling.

Reference Type: Conference Proceedings
Author: Caughlin, Don
Year: 1995
Title: Verification, Validation, and Accreditation (VV&A) of Models and Simulations through

Reduced Order Metamodels
Conference Name: 1995 Winter Simulation Conference
Editor: Alexopoulos, Christos; Kan, Keebom; Lilegdon, William R.; Goldsman, David
Conference Location: Arlington, VA
Pages: 1404-1412
Abstract: This paper provides a new approach to support Verification, Validation, and Accreditation (VV&A) of models and simulations. The need for efficient and objective methods to verify, validate and accredit models and simulations is greater than ever. More and more decisions are based on computer generated data that are derived from models and simulations. The strength of these decisions is a direct function of the validity of this data. Based on the system identification of reduced order models, this new approach approximates a complex high-dimensional model or simulation by a relatively simple mathematical model valid over a specified domain and range of interest. Verification or validation is then accomplished by the straightforward comparison of the reduced order model structure and coefficients with the baseline data or system. Well-developed identification methods and a structured procedure make this process more efficient and objective than existing methods.
Notes: Has a good summary of verification, validation, and accreditation procedures. He also discusses the use of metamodels.

Reference Type: Edited Book
Editor: Celik, I.; Freitas, C. J.
Year: 1990
Title: Benchmark Test Cases for Computational Fluid Dynamics
Publisher: The American Society of Mechanical Engineers
City: New York
Volume: FED-Vol. 93
Abstract: Multigrid Benchmark Solutions for Laminar Natural Convection Flows in Square Cavities-M. Hortmann, M. Peric, and G. Scheuerer
Compressibility Effects in Shock Wave/Homogeneous Turbulence Interaction-A. Honkan and J. Andreopoulos
A Stable, Iterative Finite-Difference Procedure for the Navier-Stokes Equations-B. S. Abdul/Nour and M. C. Potter
Predictive Software Validation Methodology for Use with Experiments Having Limited Replicability-T. LeGore
Mean Flow Field and Reynolds Stress Behavior in Co-Annular Jet Flow With Swirl Along a Centerbody-M. O. Frey and F. B. Gessner
A Benchmark for Inviscid Incompressible Flow in Spinning Containers-J. McIntyre, J. Sicilian, and J. Giezen
Experience With Benchmark Test Cases for Groundwater Flow-P. J. Roache, P. M. Knupp, S. Steinberg, and R. L. Blaine
Notes: Has a number of good papers on CFD verification.

Reference Type: Book Section
Author: Cellier, Francois E.
Year: 1984
Title: How to Enhance the Robustness of Simulation Software

C

Book Title: Simulation and Model-Based Methodologies: An Integrative View
Editor: Oren, Tuncer I.; Zeigler, Bernard P.; Elzas, Maurice S.
Publisher: Springer-Verlag Berlin Heidelberg
City: Zurich, Switzerland
Pages: 519-536
Abstract: This chapter describes different means to improve the robustness of simulation software (languages, compilers, and run-time systems) with respect to products which are currently available on the software "market".
It is shown how these improvements can help to ameliorate the robustness of models and of their coded counterparts: the simulation programs. Model robustness forms a part of the total validity picture, while simulation program robustness partly covers the correctness verification assurance.
This chapter addresses itself primarily to the simulation software designer. It is hoped that these considerations may help future software developers in producing more reliable simulation software.

Reference Type: Conference Proceedings
Author: Cole, Julian D.; Cook, L. Pamela; Schleiniger, Gilberto
Year: 1998
Title: Analysis of a Glancing Shock Moving Past a Wedge
Conference Name: 2nd AIAA Theoretical Fluid Mechanics Meeting
Conference Location: Albuquerque, NM
Volume: AIAA Paper No. 98-2688
Pages: 5
Abstract: Asymptotic analysis of an incident weak vertical shock moving past an almost horizontal thin wedge is given. The flow is assumed inviscid and irrotational. Outer and inner boundary value problems are formulated and carefully matched. The outer region, in which the flow is described to leading order by linear equations, consists of the spreading of the disturbance from the wedge tip. The inner region is confined to a neighborhood of the point where the shock and wedge meet. The governing equations in the inner region are inherently nonlinear. Regular and irregular reflection regions are identified and analyzed. Results are contrasted with previous work by other authors.
Notes: Good for verification solutions in CFD

Reference Type: Journal Article
Author: Coleman, H. W.; Stern, F.
Year: 1997
Title: Uncertainties and CFD Code Validation
Journal: Journal of Fluids Engineering
Pages: 795-803
Abstract: A new approach to computational fluid dynamics code validation is developed that gives proper consideration to experimental and simulation uncertainties. The comparison error is defined as the difference between the data and simulation values and represents the combination of all errors. The validation uncertainty is defined as the combination of the uncertainties in the experimental data and the portion of the uncertainties in the CFD prediction

that can be estimated. This validation uncertainty sets the level at which validation can be achieved. The criterion for validation is that the magnitude of the comparison error must be less than the validation uncertainty. If validation is not accomplished, the magnitude and sign of the comparison error can be used to improve the mathematical modeling. Consideration is given to validation procedures for a single code, multiple codes and/or models, and predictions of trends. Example results of verification/validation are presented for a single computational fluid dynamics code and for a comparison of multiple turbulence models. The results demonstrate the usefulness of the proposed validation strategy. This new approach for validation should be useful in guiding future developments in computational fluid dynamics through validation studies and in the transition of computational fluid dynamics codes to design.
Notes: Some good ideas for quantifying validation, however the authors do no show any awareness to the large amount of literature in statistical quantification of model validation published in the operations research community.

Reference Type: Conference Proceedings
Author: Cosner, R. R.
Year: 1995
Title: CFD Validation Requirements for Technology Transition
Conference Name: 26th AIAA Fluid Dynamics Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: San Diego, CA
Volume: AIAA Paper No. 95-2227
Abstract: Computational Fluid Dynamics technology, as a basis for design decisions, is rapidly gaining acceptance in the aerospace industry. The pace of acceptance is set by the advancing confidence of design team leaders that reliance on CFD can improve the quality of their end product, and reduce the schedule, costs and risks in developing that product. Each of these factors - quality, schedule, cost, and risk - must be suitably demonstrated prior to a prudent decision to increase reliance on CFD predictions. A key element in this continuing process of technology transition is to demonstrate improvements through a systematic validation. New standards for performance of competitive aircraft designs are leading in the requirements for CFD analysis, and in the process for validation.
Notes: Very good for practical procedures for validation.

Reference Type: Conference Proceedings
Author: Cosner, Raymond R.
Year: 1996
Title: The Role of Validation in the CFD Process at McDonnell Douglas/St. Louis
Conference Name: 19th AIAA Advanced Measurement and Ground Testing Technology Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: New Orleans, LA
Volume: AIAA Paper No. 96-2273
Pages: 16
Abstract: Validation is perhaps the major element in transitioning Computational Fluid Dynamics technology from the research and development environment to the air vehicle design

environment. Both parties in the process of technology transition must examine carefully the results of validation solutions compared with experimental data. The benefits of validation include risk mitigation, establishment of optimal design processes, and maintaining a sharp focus in research activities.
Notes: Good comments on practical application of validation in industry.

Reference Type: Conference Proceedings
Author: Cosner, Raymond R.
Year: 1998
Title: Experimental Data Needs for Risk Management in CFD Applications
Conference Name: 20th AIAA Advanced Measurement and Ground Testing Technology Conference
Conference Location: Albuquerque, NM
Volume: AIAA Paper No. 98-2781
Pages: 10
Abstract: The engineering process of CFD applications is advancing at a tremendous pace today. CFD analysis is becoming a trusted tool for engineering design. This acceptance is based on the ability of CFD analysis to produce quantitatively useful data, at consistently high levels of accuracy and process performance. The need for experimental validation data has never been higher. The requirements for focused goals and high accuracy in these experimental data also have never been higher. Almost no experimental data can be found today which meet these demanding requirements.
Notes: Good discussion of the importance of validation quality in industry.

Reference Type: Book
Author: Dahl, O.
Year: 1992
Title: Verifiable Programming
Publisher: Prentice-Hall
City: Englewood Cliff, NJ
Notes: Very good modern reference for verification

Reference Type: Report
Author: Davis, Paul K.
Year: 1992
Title: Generalizing Concepts and Methods of Verification, Validation, and Accreditation (VV&A) for Military Simulations
Institution: RAND
Report Number: R-4249-ACQ
Abstract: This study on verification, validation, and accreditation (VV&A) seeks, for military models and simulations: (a) to provide a simple and realistic framework for modelers, analysts, managers, and recipients of analysis, (b) to address important complications that have received too little attention in the past (for example, evaluation of knowledge-based models such as those representing command and control decisions and other behaviors), and (c) to discuss how modern model-building technology is changing the way we should develop models and

conduct VV&A.
Notes: This is one of the best high level descriptions of VV&A I have read. Although he doesn't specifically address types of analysis, the principles and procedures are excellent.

Reference Type: Journal Article
Author: Davis, R. T.
Year: 1967
Title: Laminar Incompressible Flow Past a Semi-Infinite Flat Plate
Journal: Journal of Fluid Mechanics
Volume: 27
Issue: 4
Pages: 691-704
Abstract: Laminar incompressible flow past a semi-infinite flat plate is examined by using the method of series truncation (or local similarity) on the full Navier-Stokes equations. The first and second truncations are calculated at points on the plate away from the leading edge, while only the first truncation is calculated at the leading edge. The solutions are compared with the results from other approximate methods.
Notes: Good paper for CFD verification.

Reference Type: Journal Article
Author: Davis, R. T.
Year: 1972
Title: Numerical Solution of the Navier-Stokes Equations for Symmetric Laminar Incompressible Flow Past a Parabola
Journal: Journal of Fluid Mechanics
Volume: 51
Issue: 3
Pages: 417-433
Abstract: Symmetric laminar incompressible flow past a parabolic cylinder is considered for all Reynolds numbers. In the limit as the Reynolds number based on nose radius of curvature goes to zero, the solution for flow past a semi-infinite flat plate is obtained. All solutions are found by using an implicit alternating direction method to solve the time-dependent Navier-Stokes equations. The solutions found are compared with various other exact and approximate solutions. Results are presented for skin friction, surface pressure, friction drag and pressure drag. The numerical method developed is of particular interest since it combines the alternating direction method with the implicit method for solving the boundary-layer equations. This leads to fast convergence and may be of use in other problems.
Notes: Good paper for CFD verification.

Reference Type: Book
Author: DeMillo, R. A.; McCracken, W. M.; Martin, R. J.; Passafiume, J. F.
Year: 1987
Title: Software Testing and Evaluation
Publisher: Benjamin/Cummings
City: Menlo Park, CA

D

Notes: Very good modern reference for verification

Reference Type: Journal Article
Author: de Vahl Davis, G.
Year: 1983
Title: Natural Convection of Air in a Square Cavity: A Benchmark Numerical Solution
Journal: International Journal for Numerical Methods in Fluids
Volume: 3
Pages: 249-264
Abstract: Details are given of the computational method used to obtain an accurate solution of the equations describing two-dimensional natural convection in a square cavity with differentially heated side walls. Second-order, central difference approximations were used. Mesh refinement and extrapolation led to solutions for $10^3 < Ra < 10^6$ which are believed to be accurate to better than 1 per cent at the higher Rayleigh number and down to one-tenth of that at the lowest value.
Notes: Classic paper on the method for obtaining high accuracy solutions for CFD verification.

Reference Type: Journal Article
Author: Dennis, S. C. R.; Walsh, J. D.
Year: 1971
Title: Numerical Solutions for Steady Symmetric Viscous Flow Past a Parabolic Cylinder in a Uniform Stream
Journal: Journal of Fluid Mechanics
Volume: 50
Issue: 4
Pages: 801-814
Abstract: Numerical solutions are presented for steady two-dimensional symmetric flow past a parabolic cylinder in a uniform stream parallel to its axes. The solutions cover the range R = 0.25 to infinity, where R is the Reynolds number based on the nose radius of the cylinder. For large R, the calculated skin friction near the nose of the cylinder is compared with known theoretical results obtained from second-order boundary-layer theory. Some discrepancy is found to exist between the present calculations and the second-order theory. For small R, it is possible to obtain a reasonably consistent check with a recent theoretical prediction for the limit of the skin friction near the nose of the cylinder as R approaches 0.
Notes: Good paper for CFD verification.

Reference Type: Journal Article
Author: Dery, Richard; Landry, Maurice; Banville, Claude
Year: 1993
Title: Revisiting the Issue of Model Validation in OR: An Epistemological View
Journal: European Journal of Operational Research
Volume: 66
Pages: 168-183
Abstract: Debates about model validation in Operational Research (OR) are both numerous and diversified. They all imply, in one way or another, the more general question of knowledge production. The problem of model validation in OR then unavoidably holds an epistemological

dimension, and it is this dimension that will be privileged here. It will be seen that three successive and rival epistemological perspectives on the production of scientific knowledge have dominated the 20th century. They are the philosophical, the historical and the sociological perspectives. Each of them brings forward an image or representation of science which sheds a particular light on the issue of model validation in OR. Moreover, it will be seen that the generally prevalent view of models and of their validation in OR can be traced back to the philosophical perspective, a perspective which has been, for many decades, widely questioned in the field of epistemology. This leads to some conclusions on the process of knowledge production in the field of epistemology. This leads to some conclusions on the process of knowledge production in the field of OR and, more particularly, on model validation. Overall, the paper aims at demonstrating the usefulness of epistemology for understanding how knowledge is produced and validated in the field of OR.
Notes: Has a very fundamental view of model validation from the philosophy of science perspective. This is the best review I have seen of the philosophical history of model validation.

Reference Type: Edited Book
Editor: Desideri, J. A.; Glowinski, R.; Periaux, J.
Year: 1991
Title: Hypersonic Flows for Reentry Problems, Vol. 1: Survey Lectures and Test Cases for Analysis
Publisher: Springer-Verlag
City: Berlin
Abstract: During this workshop, which took place in Antibes, France, in Jan. 1990, about 200 engineers and scientists from Europe, the United States, Japan and Australia presented results associated with the solution of 8 test problems. These 8 problems were carefully selected by an International Committee as representative of real life difficulties existing during the reentry of space vehicles, such as the European Hermes and the US Orbiter.
Actually, during the workshop, the technical presentations of the test problem results were completed by 10 invited lectures given by leading scientists on topics related to modeling, experimental aspects and numerical simulations of hypersonic flows.
Notes: Very good reference for verification and validation of CFD solutions in hypersonic flow.

Reference Type: Edited Book
Editor: Desideri, J. A.; Glowinski, R.; Periaux, J.
Year: 1991
Title: Hypersonic Flows for Reentry Problems, Vol. II: Test Cases-Experiments and Computations
Publisher: Springer-Verlag
City: Berlin
Abstract: During this workshop, which took place in Antibes, France, in Jan. 1990, about 200 engineers and scientists form Europe, the United States, Japan and Australia presented results associated with the solution of 8 test problems. These 8 problems were carefully selected by an International Committee as representative of real life difficulties existing during the reentry of

space vehicles, such as the European Hermes and the US Orbiter.
Problems for Analysis:
Problem 1: Flow over a slender cone
Problem 2: Turbulent base flow
Problem 3: Flow over a 2D ramp
Problem 4: Flow over a 3D obstacle
Problem 5: Corner flow
Problem 6: Double (simple) ellipsoid
Problem 7: Flow over a delta wing
Problem 8: Non-equilibrium flow in an arc jet or a shock tube
Notes: Very good reference for verification and validation of CFD solutions in hypersonic flow.

Reference Type: Book
Author: Deutsch, Michael S.
Year: 1982
Title: Software Verification and Validation
Series Title: Series in Software Engineering
Series Editor: Jensen, Randall W.
Publisher: Prentice-Hall, Inc.
Abstract: Chapter 1 Introduction
Chapter 2 Overview
Chapter 3 Control of Software Construction and Test
Chapter 4 Supplemental Testing Topics
Chapter 5 Special Testing Problems
Chapter 6 Automated Testing
Chapter 7 Application of an Automated Verification System
Part IV Verification and Validation over the Software Life Cycle
Chapter 8 Organizing the Project for Verification and Validation
Chapter 9 System Engineering Verification and Validation Activities
Chapter 10 Software Development Verification and Validation Activities
Chapter 11 Independent Test Organization Verification and Validation Activities
Chapter 12 Configuration Management/Quality Assurance Verification and Validation Activities
Chapter 13 Verification and Validation Activities Outside the Project Organization
Part V Future Trends
Chapter 14 Future Trends
Notes: Only deals with the software perspective verification and validation

Reference Type: Conference Proceedings
Author: DiMascio, A.; Paciorri, R.; Favini, B.
Year: 1998
Title: Convergence of Two Numerical Schemes for Turbulent Boundary Layer Computations
Conference Name: 29th AIAA Fluid Dynamics Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Albuquerque, NM

Volume: AIAA 98-3009
Pages: 9
Abstract: The accuracy of numerical solutions for the incompressible turbulent boundary layer past a flat plate is addressed by means of a priori and a posteriori analysis. The former is carried out by computing the exact solutions of the Reynolds averaged Navier-Stokes equations with the Baldwin-Lomax and Spalart-Allmaras models; these solutions are used for the truncation error estimate in the modified equations. The latter is performed by two different finite volume techniques, namely a centered scheme with artificial dissipation and an ENO-type scheme. The results of the a priori theoretical analysis were confirmed by a posteriori analysis of numerical solutions.
Notes: Good for verification solutions in CFD

Reference Type: Report
Author: DoD
Year: 1994
Title: DoD Directive No. 5000.59: Modeling and Simulation (M&S) Management
Institution: Department of Defense
Date: January 4, 1994
Report Number: available: www.dmso.mil/docslib/
Notes: This has the official DoD definitions of verification, validation & accreditation

Reference Type: Report
Author: DoD
Year: 1996
Title: DoD Instruction 5000.61: Modeling and Simulation (M&S) Verification, Validation, and Accreditation (VV&A)
Institution: Defense Modeling and Simulation Office, Office of the Director of Defense Research and Engr.
Date: April 29, 1996
Report Number: available: www.dmso.mil/docslib
Abstract: This Instruction implements policy, assigns responsibilities, and prescribes procedures under reference (a) [DoD Directive 5000.59] for the VV&A of DoD M&S.
Notes: This report gives the official DoD definitions of verification, validation and accreditation

Reference Type: Report
Author: DoD
Year: 1996
Title: Verification, Validation, and Accreditation (VV&A) Recommended Practices Guide
Institution: Defense Modeling and Simulation Office, Office of the Director of Defense Research and Engr.
Date: Oct. 28, 1996
Report Number: available: www.dmso.mil/docslib
Abstract: All readers will be interested in the Chapter 1 overview, particularly those sections dealing with the benefits of doing VV&A and tailoring it to contain costs.
Chapter 2 discusses basic principles of VV&A and provides amplification of the major points

contained in Chapter 1.
Chapter 3 introduces a generic VV&A and process and discusses its relationship to various types of M&S applications, including the High-Level Architecture (HLA). This chapter will be of particular interest to program managers who must integrate VV&A into their overall programs.
Chapter 4 is the technical meat of the guide, offering technical staff a host of fundamentals and techniques for performing VV&A and helping readers determine which techniques are most useful for specific types of M&S application. This section will be greatly expanded as programs mature and case studies become available.
Chapter 5 discusses the accreditation process and the work that must be done to reach a sound decision about the suitability of M&S for particular applications. It is an excellent chapter to guide the decision maker on how to plan for and implement the accreditation process and on how to integrate V&V into the decision.
Finally, Chapter 6 introduces common reporting formats for the reports that should document any VV&A effort. Although each Branch of Service may prescribe the reports it requires, this chapter provides formats that meet the common needs of all Services and thus are particularly useful when M&S is applied to a Joint requirement.
Notes: This is the most complete DOD document that explains in detail verification, validation and accreditation. The emphasis is on a systems engineering view.

Reference Type: Conference Proceedings
Author: Dolling, D. S.
Year: 1996
Title: Considerations in the Comparison of Experimental Data with Simulations Consistency of Math Models and Flow Physics
Conference Name: 27th Fluid Dynamics Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: New Orleans, LA
Volume: AIAA 96-2030
Pages: 14
Abstract: A large fraction of the experimental database used for validation of CFD predictions consists of time-averaged measurements. If meaningful conclusions are to be drawn from comparisons of these time-averaged data with computations, it is important to understand how the data are generated physically. This may be a difficult task but is an essential element in the selection of an appropriate mathematical model for the computation. In this paper some examples are given, largely for a separated compression ramp flow, of the physics underlying time-averaged wall pressure measurements and outgoing boundary-layer velocity profiles. In this particular case, flowfield unsteadiness is a dominant phenomenon, and any mathematical model which ignores this will be not useful for computing many of the parameters needed in vehicle and/or component design.

Reference Type: Journal Article
Author: Dolling, David S.
Year: 1998
Title: High-Speed Turbulent Separated Flows: Consistency of Mathematical Models and Flow Physics

Journal: AIAA Journal
Volume: 36
Issue: 5
Pages: 725-732
Abstract: A large fraction of the experimental database used for validation of computational fluid dynamics (CFD) predictions of shock-induced turbulent separated flows consists of time-averaged measurements. If meaningful conclusions are to be drawn from comparisons of these time-averaged data with computations, it is important to understand how the data are generated physically. This can be difficult and time consuming but is an essential element in the selection of an appropriate mathematical model for the computation. For the separated compression ramp interaction, which is widely used as a CFD test case, global unsteadiness is a dominant phenomenon. Without modeling the unsteadiness, accurate predictions of the time-averaged wall pressure, outgoing velocity profiles, and other parameters will likely remain elusive, irrespective of the turbulence model.

Reference Type: Book
Author: Dyer, M.
Year: 1992
Title: The Cleanroom Approach to Quality Software Development
Publisher: Wiley
City: New York
Notes: Good modern reference on verification and software quality methods.

Reference Type: Book Section
Author: Elzas, Maurice S.
Year: 1984
Title: System Paradigms as Reality Mappings
Book Title: Simulation and Model-Based Methodologies: An Integrative View
Editor: Oren, Tuncer I.; Zeigler, Bernard P.; Elzas, Maurice S.
Publisher: Springer-Verlag Berlin Heidelberg
City: The Netherlands
Pages: 41-67
Abstract: In recent years considerable progress has been made in the field of establishing and verifying the theoretical foundations of modeling and simulation. This would most naturally lead the naive observer to expect that equivalent - relevant - progress has been made in the field of unequivocally establishing unique rules for model construction and criteria for evaluating the validity of models with reference to reality.
This chapter can be considered as an attempt both to unify the different concepts which are used in this field and to demystify some exaggerated expectations. In the first place a comparison of terminology used in some important chapters that follow in the first section of this book is presented.
Next the issue of "top-down" or "bottom-up" modeling is addressed and some problems with reference to the supposed antagonism between hypothesis verification and feature extraction will be laid to rest.

E

Reference Type: Journal Article
Author: Ethier, C. Ross; Steinman, D. A.
Year: 1994
Title: Exact Fully 3D Navier-Stokes Solutions for Benchmarking
Journal: International Journal for Numerical Methods in Fluids
Volume: 19
Pages: 369-375
Abstract: Unsteady analytical solutions to the incompressible Navier-Stokes equations are presented. They are fully three-dimensional vector solutions involving all three Cartesian velocity components, each of which depends non-trivially on all three co-ordinate directions. Although unlikely to be physically realized, they are well suited for benchmarking, testing and validation of three-dimensional incompressible Navier-Stokes solvers. The use of such a solution for benchmarking purposes is described.
Notes: Good for verification solutions in CFD

Reference Type: Journal Article
Author: Fossett, C. A.; Harrison, D.; Weintrob, H.; Gass, S. I.
Year: 1991
Title: An Assessment Procedure for Simulation Models: A Case Study
Journal: Operations Research
Volume: 39
Issue: 5
Pages: 710-723

Reference Type: Book Section
Author: Foster, Harold D.
Year: 1993
Title: Resilience Theory and System Evaluation
Book Title: Verification and Validation of Complex Systems: Human Factors Issues
Editor: Wise, John A.; Hopkin, V. David; Stager, Paul
Publisher: Springer-Verlag
City: Victoria, British Columbia
Pages: 35-60
Abstract: King Ozymandias clearly failed to appreciate that, in a changing world, it is very difficult to achieve even a semblance of performance. Despite the virtual impossibility of accurately predicting the future, every decision - for example, whether to manufacture a new technology, open or close a school, hospital, or mine - implies a vision of futurity. Either implicitly or explicitly, those involved are making assumptions about such variables as social values, population growth, energy demand, prices, environmental stability, competing innovations, and political trends. None of these factors is fixed. If the past is modeled by a single straight line, then the present can be considered a dot at one end. Beyond this lies the future, not one but a multiplicity of possible alternative lines.

Reference Type: Journal Article
Author: Gartling, David K.

Year: 1990
Title: A Test Problem for Outflow Boundary Conditions-Flow Over a Backward-Facing Step
Journal: International Journal for Numerical Methods in Fluids
Volume: 11
Pages: 953-967
Abstract: A numerical solution for steady incompressible flow over a two-dimensional backward-facing step is developed using a Galerkin-based finite element method. The Reynolds number for the simulation is 800. Computations are performed on an extended channel length to minimize the effect of the outflow boundary on the upstream recirculation zones. A thorough mesh refinement study is performed to validate the results. Extensive profile data at several channel locations are provided to allow future testing and evaluation of outflow boundary conditions.
Notes: Good paper for CFD verification.

Reference Type: Journal Article
Author: Gass, Saul I.
Year: 1983
Title: Decision-Aiding Models: Validation, Assessment, and Related Issues for Policy Analysis
Journal: Operations Research
Volume: 31
Pages: 603-631
Abstract: The extension of OR decision-aiding models and OR methodology from operational and technological settings to the field of policy analysis has caused analysts and users to question whether the OR process can handle the requirements of this new area. This paper reviews the evolving nature of OR methodology, the difficulties that have arisen in applying it, and the attempts to improve the use of OR methodology in policy analysis. The analyst's role in providing information to the user to determine whether and how a specific OR model can be used as a decision aid is emphasized. Relevant information for the analyst to provide covers model validation, assessment, utility, confidence and documentation.

Reference Type: Journal Article
Author: Gass, Saul I.
Year: 1993
Title: Model Accreditation: A rationale and process for determining a numerical rating
Journal: European Journal of Operational Research
Pages: 250-258
Abstract: The proper development of a computer-based OR model includes the process by which the modeler attempts to validate the model. This is done in order to convince the modeler (who usually does not need much convincing) and others (who should require a great deal of convincing) that the model can and should be used as an aid to decision making. But to use a model for complex decision problems, we must go beyond the notion of validation. In such situations, we now hear of model assessment and evaluation, model confidence and credibility, and model certification and accreditation. A recent investigation of the modeling process produced a framework for model accreditation. Based on this work, we offer a rationale and approach for stating a level of accreditation by a numerical score.

Notes: This article provides the most detailed method for quantitatively scoring models for accreditation.

Reference Type: Conference Proceedings
Author: Gelb, Ivan L.; Nelson, Mark B.
Year: 1988
Title: Model Validation: What you Don't Know will Hurt You
Conference Name: International Conference on Management and Performance Evaluation of Computer Systems
Pages: 102-105
Abstract: Modeling packages are available which incorporate state-of-the-art queuing analysis, data manipulation, graphics, and expert systems techniques. With all this power, however, modeling prediction is only as good as the baseline model data.
This paper focuses on how to validate models quickly, leaving valuable time for forecasting and "what if" analyses. The authors provide a methodology to validate model input data and related parameters. This methodology can be used by all capacity planners prior to utilizing their model's analytical capabilities.

Reference Type: Journal Article
Author: Gervais, J. J.; Lemelin, D.; Pierre, R.
Year: 1997
Title: Some Experiments with Stability Analysis of Discrete Incompressible Flow in the Lid-Driven Cavity
Journal: International Journal for Numerical Methods in Fluids
Volume: 24
Issue: 5
Pages: 477-492
Abstract: We present results of a stability analysis of the lid-driven cavity flow based on classical C(super0) finite element discretizations of the Navier-Stokes System. Using arc length continuation and subspace iteration to compute the eigenvalues of the tangent operator, we study the dependence of the bifurcation diagram and of the spectrum on the chosen discretization.
Notes: Good paper for CFD verification.

Reference Type: Journal Article
Author: Ghia, U.; Ghia, K. N.; Shin, C. T.
Year: 1982
Title: High-Re Solutions for Incompressible Flow Using the Navier-Stokes Equations and a Multigrid Method
Journal: Journal of Computational Physics
Volume: 48
Issue: 3
Pages: 387-411
Abstract: The vorticity-stream function formulation of the two-dimensional incompressible Navier-Stokes equations is used to study the effectiveness of the coupled strongly implicit

multigrid (CSI-MG) method in the determination of high Re fine-mesh flow solutions. The driven flow in a square cavity is used as the model problem. Solutions are obtained for configurations with Reynolds number as high as 10,000 and meshes consisting of as many as 257 x 257 points. For Re = 1000 the (129 x 129) grid solution required 1.5 minutes of CPU time on the AMDAHL 470 V/6 computer. Because of the appearance of one or more secondary vortices in the flow field, uniform mesh refinement is preferred to the use of one dimensional grid clustering coordinate transformations.
Notes: Good paper for CFD verification.

Reference Type: Conference Proceedings
Author: Gosman, A. D.
Year: 1998
Title: Quality Assurance for Industrial CFD Codes
Conference Name: 29th AIAA Fluid Dynamics Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Albuquerque, NM
Volume: AIAA 98-2637
Pages: 9
Abstract: An overview is provided of the various factors which influence the quality of industrial CFD codes and the results which they produce. It is argued that important quality issues arise in the basic methodology development, in code assembly and in application. Discretization, physics modelling and input data errors are identified as the main contributors. Some suggestions are offered on how to reduce these.
Notes: Has a very good discussion of verification and validation procedures in CFD.

Reference Type: Conference Proceedings
Author: Graves, Randolph, Jr.
Year: 1992
Title: Software Validation: The Bridge from R&D to Industrial Application
Conference Name: 30th Aerospace Sciences Meeting & Exhibit
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Reno, NV
Volume: AIAA 92-0587
Pages: 10
Abstract: The development of applications software proceeds through well defined phases from its initial R&D character to maturity. This paper reviews this process and correlates the relevant stages so that the critical steps are identified. The most critical step is the pilot code stage which is the point in the development process that becomes a gap between the developers and end users of applications software. This is the point in the process where the calibration and validation of the software becomes the key step in the maturation process. To bridge this gap the validation process requires careful management and there are several simple management tools reviewed that can assist the programmer or manager in guiding the applications software development. These simple management tools can assure that mature software is developed which can meet the industrial user's need for applicable, reliable and usable engineering applications software.

G

Reference Type: Conference Proceedings
Author: Grenda, J. M.; Schwer, D. A.; Merkle, C. L.
Year: 1996
Title: Use of Analytical Solutions in Validating Unsteady CFD Codes
Conference Name: 1st AIAA Theoretical Fluid Mechanics Meeting
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: New Orleans, LA
Volume: AIAA-96-2164
Pages: 12
Abstract: The validation of unsteady CFD codes by comparison with closed-form analytical solutions is discussed. The approach considers unsteady oscillatory solutions that grow or decay with time as in classical stability problems. The analytical solutions can be used to determine the accuracy of unsteady CFD computations. The first example is an unsteady shear layer with heat release, and the second example considers chamber oscillations characteristic of combustion instability. The solution procedures are straightforward and may be employed on a workstation or PC at minimum computational expense.
Notes: Very good for verifying CFD codes using analytical solutions

Reference Type: Journal Article
Author: Gresho, P. M.; Gartling, D. K.; Torczynski, J. R.; Cliffe, K. A.; Winters, K. H.; Garratt, J. T.; Spence, A.; Goodrich, J. W.
Year: 1993
Title: Is the Steady Viscous Incompressible Two-Dimensional Flow Over a Backward-Facing Step at Re=800 Stable?
Journal: International Journal for Numerical Methods in Fluids
Volume: 17
Pages: 501-541
Abstract: A detailed case study is made of one particular solution of the 2D incompressible Navier-Stokes equations. Careful mesh refinement studies were made using four different methods (and computer codes): (1) a high-order finite difference method solving the unsteady equations by time-marching; (2) a high-order finite-element method solving both the steady equations and the associated linear-stability problem; (3) a second-order finite difference method solving the unsteady equations in streamfunction form by time-marching; and (4) a spectral-element method solving the unsteady equations by time-marching. The unanimous conclusion is that the correct solution for flow over the backward-facing step at Re = 800 is steady-and it is stable, to both small and large perturbations.
Notes: Good paper for CFD verification.

Reference Type: Conference Proceedings
Author: Gruhl, James
Year: 1979
Title: Model Validation
Publisher: Institute of Electrical and Electronics Engineers
Pages: 536-541
Abstract: With the use of increasingly complex models of energy systems, as well as in many

other fields, it is becoming increasingly apparent that there is tremendous variation in the range and degree of validity of these models. This paper presents discussions and examples of a number of techniques that can be useful in assessments of model validity. In addition there is a discussion of the topic of quantifying the predictive quality of a model with respect to a given application; this may be viewed as the ultimate model assessment achievement. Finally, because assessment activities are likely to be severely constrained by available funding, time, and manpower resources, suggestions are presented for facilitating the development of systematic assessment strategies that are tailored to the model's important characteristics.
Notes: Has an early view of the stages in modeling and simulation. Has some suggestions for procedures for verification and validation. Mainly deals with energy models.

Reference Type: Journal Article
Author: Guerrero, J. S. P.; Cotta, R. M.
Year: 1992
Title: Integral Transform Solution for the Lid-Driven Cavity Flow Problem in Streamfunction-Only Formulation
Journal: International Journal for Numerical Methods in Fluids
Volume: 15
Issue: 4
Pages: 399-409
Abstract: The basic ideas in the generalized integral transform technique are further advanced to allow for the hybrid numerical-analytical solution of the two-dimensional steady Navier-Stokes equations in streamfunction only formulation. The classical lid-driven square cavity problem is selected for illustration of the approach. The corresponding biharmonic-type non-linear partial differential equation for the streamfunction is integral transformed in one of the coordinates and an infinite system of coupled non-linear ODEs for the transformed potential results in the other independent variable. Upon truncation to an appropriate finite order, the ODE system is numerically solved by well-established algorithms with automatic error control devices. The convergence behavior of the eigenfunction expansion is demonstrated and reference results are provided for typical values of Reynolds number.
Notes: Good paper for CFD verification.

Reference Type: Journal Article
Author: Guerrero, J. S. Perez; Cotta, R. M.
Year: 1996
Title: Benchmark Integral Transform Results for Flow Over a Backward-Facing Step
Journal: Computers and Fluids
Volume: 25
Issue: 5
Pages: 527-540
Abstract: Benchmark results for flow over a backward-facing step are obtained through the so-called generalized integral transform technique (GITT). This hybrid numerical-analytical approach is employed to handle the steady two-dimensional incompressible Navier-Stokes equations in streamfunction-only formulation. Numerical results with automatic global accuracy control are produced for different values of Reynolds number. Critical comparisons

with previously reported experimental results are performed with excellent agreement. Also, a few different purely numerical approaches are validated, from a survey of the recent literature.
Notes: Good paper for CFD verification.

Reference Type: Book Section
Author: Hancock, P. A.
Year: 1993
Title: On the Future of Hybrid Human-Machine Systems
Book Title: Verification and Validation of Complex Systems: Human Factors Issues
Editor: Wise, John A.; Hopkin, V. David; Stager, Paul
Publisher: Springer-Verlag
City: Minneapolis, Minnesota
Pages: 61-85
Abstract: I propose to consider the question, what is the future of hybrid human-machine systems? In the present context, hybrid human-machine systems are those in which human and machine have to engage in some form of collaborative action in order to achieve a defined goal. As the basis for this effort, I examine the contemporary status of human-machine interaction against the background of a paradigmatic evolution that is occurring in how complex technical interaction can be understood. In examining issues associated with verification and validation of existing and planned large-scale integrated systems, I point to the impact that innovations in both theoretical approach and technological instantiation will have on the design and use of future technology. I begin by examining the global forces which drive such technical developments and illustrate potential and actual roles that humans currently play with respect to machines. I posit that the evolution of human-machine interaction explains how a prescription based solely on an understanding of human cognition is unlikely to succeed to the desired degree, at least in a timely manner. I point to the reciprocity of complexity between the evolution of contemporary understanding of human and machine and turn to the critical issue of intention in systems design and operation.

Reference Type: Journal Article
Author: Hansen, E. B.; Kelmanson, M. A.
Year: 1994
Title: An Integral Equation Justification of the Boundary Conditions of the Drive-Cavity Problem
Journal: Computers and Fluids
Volume: 23
Issue: 1
Pages: 225-240
Abstract: The driven-cavity problem, a renowned bench-mark problem of computational, incompressible fluid dynamics, is physically unrealistic insofar as the inherent boundary singularities (where the moving lid meets the stationary walls) imply the necessity of an infinite force to drive the flow: this follows from G. I. Taylor's analysis of the so-called scraper problem. Using a boundary integral equation (BIE) formulation employing a suitable Green's function, we investigate herein, in the Stokes approximation, the effect of introducing small "leaks" to replace the singularities, thus rendering the problem physically realizable. The BIE

approach used here incorporates functional forms of both the asymptotic far-field and singular near-field solution behaviors, in order to improve the accuracy of the numerical solution. Surprisingly, we find that the introduction of the leaks affects notably the global flow field a distance on the order of 100 leak widths away from the leaks. However, we observe that, as the leak width tends to zero, there is excellent agreement between our results and Taylor's, thus justifying the use of the seemingly unrealizable boundary conditions in the driven-cavity problem. We also discover that the far-field, asymptotic, closed-form solution mentioned above is a remarkably accurate representation of the flow even in the near-field. Several streamline plots, over a range of spatial scales, are presented.
Notes: Good paper for CFD verification.

Reference Type: Conference Proceedings
Author: Hasselman, T. K.; Chrostowski, J. D.
Year: 1997
Title: Effects of Product and Experimental Variability on Model Verification of Automobile Structures
Conference Name: Proceedings of the 15th International Modal Analysis Conference
Publisher: Society for Experimental Mechanics
Conference Location: Orlando, FL
Pages: 612-620
Abstract: Experimental verification of a structural dynamic model requires vibration testing to obtain frequency response and model data. The data are used to refine the model and assess its predictive accuracy. Although the existence of product variability and experimental variability are acknowledged, they are typically ignored in the model verification process. Models are "tuned" to match a particular set of data, usually by trial and error, and used to evaluate structural performance deterministically. Predictive accuracy is assessed heuristically, if at all. This paper describes an effort to quantify product and experimental variability based on multiple tests of multiple automobiles of the same design. These data are used to evaluate the modeling uncertainty and predictive accuracy of structural dynamic models updated by statistical parameter estimation. Quantitative results on product variability and experimental variability are presented, along with their effects on the predictive accuracy of the model.
Notes: Hasselman's perspective is very good in trying to quantify the uncertainty in structural dynamics simulations, not just rely on parameter identification after the fact. However, he has a very different understanding of verification vs validation.

Reference Type: Journal Article
Author: Hatton, Les
Year: 1997
Title: The T Experiments: Errors in Scientific Software
Journal: IEEE Computational Science & Engineering
Pages: 27-38
Abstract: Extensive tests showed that many software codes widely used in science and engineering are not as accurate as we would like to think. Better software engineering practices would help solve this problem, but realizing that the problem exists is an important first step.
Notes: The author conducted the most comprehensive study of software quality tests and

verification tests on scientific software. He shows that there should be very serious concerns about the accuracy of all scientific codes.

Reference Type: Conference Proceedings
Author: Haynes, T. S.; Reed, H. L.; Saric, W. S.
Year: 1996
Title: CFD Validation Issues in Transition Modeling
Conference Name: 27th AIAA Fluid Dynamics Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: New Orleans, LA
Volume: AIAA Paper No. 96-2051
Pages: 24
Abstract: Laminar-turbulent transition is highly initial-condition and operating-condition dependent. Finding careful, archival experiments for comparison is the main validation issue; few exist. The CFD formulations validated to date demonstrate that if the environment and operating conditions can be modelled and input correctly, the computations (nonlinear PSE and DNS) agree quantitatively with the experiments. Future challenges for validation include: Successful CFD simulations of available complete databases; CFD leadership in the identification, cataloging, and modeling of the effects of freestream disturbances; CFD leadership in the determination of relevant validation experiments for supersonic and hypersonic flows; careful validation experiments and CFD solutions for complex 3-D geometries; and simulations and validations for the high Reynolds numbers of flight.

Reference Type: Report
Author: Hodges, James S.; Dewar, James A.
Year: 1992
Title: Is it You or Your Model Talking? A Framework for Model Validation
Institution: RAND
Date: 1992
Report Number: R-4114-AF/A/OSD
Abstract: The problem of model validation is still with us. Why? Defense modelers seem to agree that validation has something to do with comparing models to reality, but disagree about how to go about it. The problem flows from a presumption that all models - be they of fuze activation or theater-level combat - can be validated and that a single validation standard and procedure can and should be defined. We believe that this presumption is a fundamental error: Some models can be validated and used to predict, while others cannot be validated and may only be put to nonpredictive uses. With this distinction, it is straightforward to define validation for validatable models and to define standards of evaluation for nonpredictive uses of unvalidatable or unvalidated models. Without this distinction, people modeling fuzes and theater-level combat will talk past each other forever, because their problems are fundamentally different.
Notes: One of the best descriptions of the fundamental requirements of modeling and simulation validation from a systems point of view.

Reference Type: Conference Proceedings
Author: Holden, M. S.; Moselle, J. R.

Year: 1992
Title: A Database of Aerothermal Measurements in Hypersonic Flow for CFD Validation
Conference Name: AIAA 17th Aerospace Ground Testing Conf.
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Nashville, TN
Volume: AIAA Paper No. 92-4023
Abstract: This paper presents an experimental database selected and compiled from aerothermal measurements obtained on basic model configurations on which fundamental flow phenomena could be most easily examined. The experimental studies were conducted in hypersonic flows in Calspan's 48-inch, 96-inch, and 6-foot shock tunnels during the past 25 years. The measurements selected for this database were assembled from a far larger data set by choosing only the measurements in laminar, transitional, and turbulent flows, which we believe are of the greatest value for code validation. A special computer program, "CUBDAT," was constructed to provide easy access to the measurements in the database as well as the means to plot the measurements and compare them with imported data. The database contains tabulations of model configurations; freestream conditions; and measurements of heat transfer, pressure, and skin friction for each of the studies selected for inclusion.

Reference Type: Conference Proceedings
Author: Holden, M. S.; Moselle, J. R.; Sweet, S. J.; Martin, S. C.
Year: 1996
Title: A Database of Aerothermal Measurements in Hypersonic Flow for CFD Validation
Conference Name: AIAA 7th International Space Planes and Hypersonic Systems and Technologies Conf.
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Norfolk, VA
Volume: AIAA Paper No. 96-4597
Abstract: This paper presents an experimental database selected and compiled from aerothermal measurements obtained in hypersonic flow on simple model configurations on which fundamental flow phenomena could be most easily examined. The experimental studies were conducted at Mach numbers between 6 and 18 in the Calspan shock tunnels and the Large Energy National Shock (LENS) facility. The measurements selected for this database were assembled from a much larger data set by choosing only the measurements in laminar, transitional, and turbulent flows, which are of the greatest value for code validation, and for which the model and flowfield boundary conditions are well established. A computer program, "CUBDAT," was constructed specifically to provide easy access to the model and freestream measurements in the database, as well as the means to plot the measurements and compare them with imported data. The database contains diagrams of model configurations and tabulations of freestream conditions, measurements of heat transfer, pressure, and skin friction for each of the studies selected.
Notes: This is a very good database for aerothermal validation in CFD.

Reference Type: Book Section
Author: Hollnagel, Erik
Year: 1993

H

Title: The Reliability of Interactive Systems: Simulation Based Assessment
Book Title: Verification and Validation of Complex Systems: Human Factors Issues
Editor: Wise, John A.; Hopkin, V. David; Stager, Paul
Publisher: Springer-Verlag
City: Denmark
Pages: 205-221
Abstract: Technological systems today are highly dependent on the interaction between humans and machines. The reliability of this interaction is consequently essential for the reliability of the joint system. The systematic study of how this interaction can be analyzed, described, and designed and how the reliability can be assessed is therefore of primary importance. Regardless of whether the interaction is seen as a temporary necessity due to the lack of complete automation or as an essential aspect of the system's functionality, there are three main problems that face practitioners in the field of Man-Machine Interaction (MMI).

Reference Type: Book Section
Author: Hopkin, V. David
Year: 1993
Title: Verification and Validation: Concepts, Issues, and Applications
Book Title: Verification and Validation of Complex Systems: Human Factors Issues
Editor: Wise, John A.; Hopkin, V. David; Stager, Paul
Publisher: Springer-Verlag
City: Farnborough, England
Pages: 9-33
Abstract: Technological advances and innovations lead to the creation of new human-machine systems, and to the evolution or replacement of existing systems, in the pursuit of enhanced safety, capacity or efficiency. These technical developments expand the range of options available in the design and implementation of large human-machine systems. Increased integration, interdependence and complexity seem to have become hallmarks of progress in such systems. The pace of progress can outstrip the identification and consideration of all its implications.
It is necessary, in dealing with the processes of verification and validation in systems, to accept a challenge, solve a puzzle, and resolve a paradox. The challenge is to assemble and appraise theoretical and practical knowledge of current and previous work on verification and validation, in order to gauge its worth and applicability and to suggest future policies and practices. The puzzle is why verification and validation activities have waned as the apparent need for them has increased. The paradox is the potential production of conclusions and recommendations about verification and validation which themselves are unverified and unvalidated.

Reference Type: Journal Article
Author: Hortmann, M.; Peric, M.; Scheuerer, G.
Year: 1990
Title: Finite Volume Multigrid Prediction of Laminar Natural Convection: Bench-Mark Solutions
Journal: International Journal for Numerical Methods in Fluids
Volume: 11

Pages: 189-207
Abstract: A finite volume multigrid procedure for the prediction of laminar natural convection flow is presented, enabling efficient and accurate calculations on very fine grids. The method is fully conservative and uses second-order central differencing for convection and diffusion fluxes. The calculations start on a coarse (typically 10x10 control volumes) grid and proceed to finer grids until the desired accuracy or maximum affordable storage is reached. The computing times increase thereby linearly with the number of control volumes.
Solutions are presented for the flow in a closed cavity with side walls at different temperatures and insulated top and bottom walls. Rayleigh numbers of 10^4, 10^5, and 10^6 are considered. Grids as fine as 640x640 control volumes are used and the results are believed to be accurate to within 0.01%. Second-order monotonic convergence to grid-independent values is observed for all predicted quantities.
Notes: Very good paper for CFD code verification.

Reference Type: Edited Book
Editor: Hughes, Wayne P.; Battilega, John A.; Brown, Thomas A.; Bryson, Marion R.; Drezner, Stephan M.; Englund, John A.; Friel, John; Grange, Judith K.; Hallex, Robert A.; Hillestad, Richard J.; Leibholz, Stephen W.; Lieberman, Alfred; Martin, James J.; Payne, Wilbur B.; Rostker, Bernard D.; Thomas, Clayton J.
Year: 1984
Title: Military Modeling
Publisher: The Military Operations Research Society, Inc.
Abstract: The aim of the Overview is to discuss orthodox military modeling. The committee endeavored to collate the collective wisdom and experience of the profession, debating not their own predispositions, but what they ascribed to be the beliefs held by the military operations research community as a whole. Doubtless they failed in some particulars. Still I would emphasize that they found a surprisingly large set of commonly held lore, insights, and judgments. Moreover there may be underway a further convergence of views. This monograph may well serve to hasten that process.
One of the early substantive focus points of this monograph was to put in better perspective what is variously called validation and verification. I believe the monograph achieves this aim. The Overview, with its concept of "corroboration" as the more accurate term, Clayton Thomas' Chapter 13, and Wilbur Payne's Chapter 14, together serve as a needed reference point for future discussions. The monograph is not the last word, but it is certainly a suitable first word by MORS on the subject of verification and validation.
Notes: Has some very good fundamental ideas about modeling complex processes. They use the opposite definition of verification and validation from DMSO.

Reference Type: Report
Author: IEEE
Year: 1984
Title: ANSI/IEEE Std 100-1984: IEEE Standard Dictionary of Electrical and Electronics Terms
Date: 1984
Notes: The IEEE definitions for verification and validation are significantly different than the

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DMSO definitions.

Reference Type: Report
Author: IEEE
Year: 1991
Title: IEEE Standard Glossary of Software Engineering Terminology
Institution: IEEE
Date: Feb. 1991
Report Number: IEEE Std 610.12-1990
Abstract: The computer field is continuing to expand. New terms are being generated and new meanings are being adopted for existing terms. The IEEE Computer Dictionary project was undertaken to document this vocabulary. Its purpose is to identify terms currently in use in the computer field and to establish standard definitions for these terms. The dictionary is intended to serve as a useful reference for those in the computer field and for those who come into contact with computers either through their work or in their everyday lives.
Notes: This is the best engineering society reference on terminology for modeling and simulation. However, IEEE definitions for verification and validation are significantly different than the DMSO definitions.

Reference Type: Report
Author: ISO
Year: 1993
Title: Guide to the Expression of Uncertainty in Measurement
Institution: International Standards Org.
Date: 1993
Report Number: ISBN 92-67-10188-9
Notes: Good for experimental data uncertainty estimation for validation.

Reference Type: Conference Proceedings
Author: Jameson, A.; Martinelli, L.
Year: 1996
Title: Mesh Refinement and Modeling Errors in Flow Simulation
Conference Name: 27th AIAA Fluid Dynamics Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: New Orleans, LA
Volume: AIAA 96-2050
Pages: 25
Abstract: This paper presents a perspective on verification and validation of computational fluid dynamics tools for analysis and design. It identifies principal sources of error due to approximations in the physical model, numerical discretization, and implementation. Issues in algorithm design and trade-offs between modelling accuracy and computational costs are discussed in detail. Computational examples are drawn from the authors' work in several applications areas.
Notes: Has some good points about the difficulty of finding programming errors.

Reference Type: Journal Article
Author: Jameson, Antony; Martinelli, Luigi
Year: 1998
Title: Mesh Refinement and Modeling Errors in Flow Simulation
Journal: AIAA Journal
Volume: 36
Issue: 5
Pages: 676-686
Abstract: This paper presents a perspective on verification and validation of computational fluid dynamics tools for analysis and design. It identifies principal sources of error due to approximations in the physical model, numerical discretization, and implementation. Issues in algorithm design and tradeoffs between modeling accuracy and computational costs are discussed. Computational examples are drawn from the authors' work.

Reference Type: Conference Proceedings
Author: Kammeyer, Mark E.
Year: 1998
Title: Wind Tunnel Facility Calibrations and Experimental Uncertainty
Conference Name: 20th AIAA Advanced Measurement and Ground Testing Technology Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Albuquerque, NM
Volume: AIAA 98-2715
Pages: 6
Abstract: The impact of facility calibrations on wind tunnel test results is addressed. It is shown that this error source can be the dominant contributor to the total experimental uncertainty. Examples are presented for transonic and supersonic cases, demonstrating the inclusion of this term without the introduction of false correlations among error sources. The importance of documentation detailing the uncertainty analysis is emphasized.
Notes: Very good for experimental uncertainty estimation in validation data

Reference Type: Journal Article
Author: Karniadakis, G. E.; Triantafyllou, G. S.
Year: 1992
Title: Three-Dimensional Dynamics and Transition to Turbulence in the Wake of Bluff Objects
Journal: Journal of Fluid Dynamics
Volume: 238
Pages: 1-30
Abstract: The wakes of bluff objects and in particular of circular cylinders are known to undergo a 'fast' transition, from a laminar two-dimensional state at Reynolds number 200 to a turbulent state at Reynolds number 400. The process has been documented in several experimental investigations, but the underlying physical mechanisms have remained largely unknown so far. In this paper, the transition process is investigated numerically, through direct simulation of the Navier-Stokes equations at representative Reynolds numbers, up to 500. A high-Order time-accurate, mixed spectral/spectral element technique is used. It is shown that

the wake first becomes three-dimensional, as a result of a secondary instability of the two-dimensional vortex street. This secondary instability appears at a Reynolds number close to 200. For slightly supercritical Reynolds numbers, a harmonic state develops, in which the flow oscillates at its fundamental frequency (Strouhal number) around a spanwise modulated time-average flow. In the near wake the modulation wavelength of the time-average flow is half of the spanwise wavelength of the perturbation flow, consistently with linear instability theory. The vortex filaments have a spanwise wavy shape in the near wake, and form rib-like structures further downstream. At higher Reynolds numbers the three-dimensional flow oscillation undergoes a period-doubling bifurcation, in which the flow alternates between two different states. Phase-space analysis of the flow shows that the basic limit cycle has branched into two connected limit cycles. In physical space the period doubling appears as the shedding of two distinct types of vortex filaments.
Further increases of the Reynolds number result in a cascade of period-doubling bifurcations, which create a chaotic state in the flow at a Reynolds number of about 500. The flow is characterized by broadband power spectra, and the appearance of intermittent phenomena. It is concluded that the wake undergoes transition to turbulence following the period-doubling route.
Notes: Good paper for CFD verification.

Reference Type: Journal Article
Author: Kashiwagi, Masahide; Oishi, Shin'ichi
Year: 1995
Title: Numerical Validation Method for Nonlinear Equations Using Interval Analysis and Rational Arithmetic
Journal: Electronics and Communications
Volume: 78
Issue: 7
Pages: 99-112
Abstract: This paper proposes an algorithm with a guaranteed accuracy for the finite-dimensional nonlinear equation. First, an algorithm is shown which can determine the interval containing the true solution, based on the given approximate solution. The method is based on the interval analysis and considers the representation error of the equation. Then the interval iteration method is shown which can arbitrarily reduce the interval. The rational number arithmetic is used and the rounding of the rational number is utilized effectively. Finally, an experimental implementation of the algorithm on a computer is presented, together with some numerical examples.

Reference Type: Report
Author: Ketelle, R. H.; Lee, R. R.; Bownds, J. M.; Rizk, T. A.
Year: 1989
Title: Model Validation Lessons Learned: A Case Study at Oak Ridge National Laboratory
Institution: Oak Ridge National Laboratory
Report Number: CONF-89085406/DE89 015900
Abstract: A groundwater flow and contaminant transport model validation study was performed to determine the applicability of typical groundwater flow models for performance assessment

of proposed waste disposal facilities at Oak Ridge, Tennessee. Standard practice site interpretation and groundwater modeling resulted in inaccurate predictions of contaminant transport at a proposed waste disposal site. The site's complex and heterogeneous geology, the presence of flow dominated by fractured and weathered zones, and the strongly transient character of shallow aquifer recharge and discharge combined to render assumptions of steady-state, homogeneous groundwater flow invalid.

Reference Type: Conference Proceedings
Author: Kleijnen, J. P. C.
Year: 1995
Title: Sensitivity Analysis and Related Analyses; A Survey of Statistical Techniques
Conference Name: International Symposium: Theory and Applications of Sensitivity Analysis of Model Output in Computer Simulation
Conference Location: Belgirate, Italy
Pages: 17
Abstract: This paper reviews the state of the art in five related types of analysis, namely (i) sensitivity or what-if analysis, (ii) uncertainty or risk analysis, (iii) screening, (iv) validation, and (v) optimization. The main question is: when should which type of analysis be applied; which statistical techniques may then be used? This paper distinguishes the following five stages in the analysis of a simulation model. 1) Validation: the availability of data on the real system determines which type of statistical technique to use for validation. 2) Screening: in the simulation's pilot phase the really important inputs can be identified through a novel technique, called sequential bifurcation, which uses aggregation and sequential experimentation. 3) Sensitivity analysis: the really important inputs should be subject to a more detailed analysis, which includes interactions between these inputs; relevant statistical techniques are design of experiments (DOE) and regression analysis. 4) Uncertainty analysis: the important environmental inputs may have values that are not precisely known, so the uncertainties of the model outputs that result from the uncertainties in these model inputs should be quantified; relevant techniques are the Monte Carlo method and Latin hypercube sampling. 5) Optimization: the controllable inputs should be steered; a relevant technique is Response Surface Methodology (RSM), which combines DOE, regression analysis and steepest-ascent hill-climbing. This approach with its five stages implies that sensitivity analysis should precede uncertainty analysis. This paper briefly discusses several case studies for each phase.

Reference Type: Journal Article
Author: Kleijnen, Jack P. C.
Year: 1995
Title: Verification and Validation of Simulation Models
Journal: European Journal of Operational Research
Volume: 82
Pages: 145-162
Abstract: This paper surveys verification and validation of models, especially simulation models in operations research. For verification it discusses 1) general good programming practice (such as modular programming), 2) checking intermediate simulation outputs through tracing and statistical testing per module, 3) statistical testing of final simulation outputs against

analytical results, and 4) animation. For validation it discusses 1) obtaining real-world data, 2) comparing simulated and real data through simple tests such as graphical, Schruben-Turing, and t tests, 3) testing whether simulated and real responses are positively correlated and moreover have the same mean, using two new statistical procedures based on regression analysis, 4) sensitivity analysis based on design of experiments and regression analysis, and risk or uncertainty analysis based on Monte Carlo Sampling, and 5) white versus black box simulation models. Both verification and validation require good documentation, and are crucial parts of assessment, credibility, and accreditation. A bibliography with 61 references is included.
Notes: Has one of the most up-to-date reviews of the steps in V&V. Even though it is directed mainly toward OR, he gives a very good discussion of verification and validation procedures.

Reference Type: Conference Proceedings
Author: Kleijnen, Jack P. C.; Bettonvil, Bert; Van Groenendahl, Willem
Year: 1996
Title: Validation of Trace-Driven Simulation Models: Regression Analysis Revisited
Conference Name: 1996 Winter Simulation Conference Proceedings
Editor: Charnes, John M.; Morrice, Douglas J.; Brunner, Daniel T.; Swain, James J.
Conference Location: Coronado, California
Pages: 351-359
Abstract: For the validation of trace-driven simulation models this paper recommends a simple statistical test that uses elementary regression analysis in a novel way. This test concerns a (joint) null-hypothesis: the outputs of the simulated and the real systems have the same means and the same variances. Technically, the differences between simulated and real outputs are regressed on their sums, and the resulting slope and intercept are tested to be zero. This paper further proves that it is wrong to use a naive test that regresses the simulation outputs on the real outcomes, and hypothesizes that the resulting regression line gives a 45 degree line through the origin. The new and the old tests are investigated in Monte Carlo experiments with inventory systems. The conclusion is that the new test has the correct type I error probability, whereas the old test (falsely) rejects a valid simulation model substantially more often than the nominal alpha level. The power of the new test increases, as the simulation model deviates more from the real system.
Notes: Mainly deals with discrete event simulation

Reference Type: Book
Author: Kleijnen, Jack P. C.; van Groenendaal, Willem
Year: 1988
Title: Simulation: A Statistical Perspective
Publisher: John Wiley & Sons
City: New York
Edition: 1st
Abstract: Ch. 1 Introduction
Ch. 2 Random Numbers
Ch. 3 Sampling from Non-uniform Distributions
Ch. 4 Economic and Corporate Models

Ch. 5 Operations Research Models
Ch. 6 Simulation Software
Ch. 7 Statistical Applications
Ch. 8 Regression Metamodels
Ch. 9 Design of Experiments
Ch. 10 Tactical Aspects
Ch. 11 Verification and Validation
Notes: Mainly deals with statistical aspects of simulation of economic and business systems.

Reference Type: Journal Article
Author: Kleijnen, Jack P. C.
Year: 1995
Title: Statistical Validation of Simulation Models
Journal: European Journal of Operational Research
Pages: 21-34
Abstract: Rigorous statistical validation requires that the responses of the model and the real system have the same expected values. However, the modeled and actual responses are not comparable if they are obtained under different scenarios (environmental conditions). Moreover, data on the real system may be unavailable; sensitivity analysis can then be applied to find out whether the model inputs have effects on the model outputs that agree with the experts' intuition. Not only the total model, but also its modules may be submitted to such sensitivity analyses. This article illustrates these issues through a case study, namely a simulation model for the use of sonar to search for mines on the sea bottom. The methodology, however, applies to models in general.
Notes: Has good recent references

Reference Type: Book
Author: Knepell, Peter L.; Arangno, Deborah C.
Year: 1993
Title: Simulation Validation: A Confidence Assessment
Publisher: IEEE Computer Society Press
City: Washington
Edition: 1st
Abstract: Ch. 1 Introduction
Ch. 2 Foundations
Ch. 3 Assessment Activities
Ch. 4 A Guide to Formal Assessment
Ch. 5 A Guide to Limited and Maintenance Assessments
Ch. 6 Man-in-the-Loop Models
Ch. 7 Hardware-in-the-Loop Models
Ch. 8 Assessment Aids
Notes: Has a very good description of the software quality steps in V&V.

Reference Type: Journal Article
Author: Landry, Maurice; Malouin, Jean-Louis; Oral, Muhittin
Year: 1983

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Title: Model Validation in Operations Research
Journal: European Journal of Operational Research
Volume: 14
Pages: 207-220
Abstract: Numerous articles have appeared in the literature expressing different degrees of concern with the methodology of OR in general and with the validation of OR models in particular. Suggestions have been formulated to remove some of the shortcomings of the methodology as currently practiced and to introduce modifications in the approach because of the changing nature of the problems tackled. Advances in modeling capabilities and solution techniques have also had considerable impact on the way validation is perceived. Large scale computer-based, mathematical models and especially simulation models have brought new dimensions to the notion of validation. Terms like confidence credibility and reliability, model assessment and evaluation, usefulness and usability of the model have become rather common. This paper is an attempt, through an interpretation of the literature, to put model validation and related issues in a framework that may be of use both to model-builders and to decision-makers.
Notes: They give an excellent history and perspective of model validation in OR. Much of it is appropriate to M&S in computational physics

Reference Type: Journal Article
Author: Landry, Maurice; Oral, Muhittin
Year: 1993
Title: In Search of a Valid View of Model Validation for Operations Research
Journal: European Journal of Operational Research
Pages: 161-167
Abstract: We present a general perspective for the purpose of positioning each paper that appears in this Special Issue on "Model Validation in Operational Research". We also raise the question of why the problem of model validation resurfaces from time to time. The pertinent literature suggests that model validation has traditionally been treated from the perspective of efficiency (doing things right). The perspective of effectiveness (doing the right things), on the other hand, has been neglected or completely ignored. This Special Issue is more on the side of effectiveness. The effectiveness perspective addresses itself to the basic question of knowing what a valid model is about and thus necessarily referring to the field of epistemology. Within this general framework, each paper appearing in this special issue is very briefly presented and commented on.
Notes: Excellent summary and critique of seven papers that appear in this issue of the European Journal of Operational Research.

Reference Type: Conference Proceedings
Author: Lee, Lawton H.; Poolla, Kameshwar
Year: 1994
Title: Statistical Validation for Uncertainty Models
Conference Name: Feedback Control, Complexity, and Identification: A festschrift for Professor George Zames
Editor: Thoma, M.

Publisher: Springer-Verlag
Conference Location: Montreal, Canada
Volume: Lecture Notes in Control and Information Sciences, Vol. 202
Pages: 131-149
Abstract: Statistical model validation is treated for a class of parametric uncertainty models and also for a more general class of nonparametric uncertainty models. We show that, in many cases of interest, this problem reduces to computing relative weighted volumes of convex sets in R (where N is the number of uncertain parameters) for parametric uncertainty models, and to computing the limit of a sequence of relative weighted volumes of convex sets in R for nonparametric uncertainty models. We then present and discuss a randomized algorithm based on gas kinetics for probable approximate computation of these volumes. We also review the existing Hit-and-Run family of algorithms for this purpose.
Notes: Has some good statistical definitions of model validation

Reference Type: Journal Article
Author: Lee, L. H.; Poolla, K.
Year: 1996
Title: On Statistical Model Validation
Journal: Journal of Dynamic Systems, Measurement and Control
Volume: 118
Pages: 226-236
Abstract: In this paper we formulate a particular statistical model validation problem in which we wish to determine the probability that a certain hypothesized parametric uncertainty model is consistent with a given input-output data record. Using a Bayesian approach and ideas from the field of hypothesis testing, we show that in many cases of interest this problem reduces to computing relative weighted volumes of convex sets in Rn (where N is the number of uncertain parameters). We also present and discuss a randomized algorithm based on gas kinetics, as well as the existing Hit-and-Run family of algorithms, for probable approximate computation of these volumes.
Notes: They deal with the question of how is quantitative confidence built in modeling and simulation. They use statistical methods to build confidence.

Reference Type: Conference Proceedings
Author: LeGore, T.
Year: 1990
Title: Benchmark Test Cases for Computational Fluid Dynamics
Conference Name: 1990 Spring Meeting of the Fluids Engineering Division
Editor: Celik, I.; Freitas, C. J.
Publisher: American Society of Mechanical Engineers
Conference Location: Toronto, Ontario
Volume: FED-Vol. 93
Pages: 21-27
Abstract: In a cooperative effort, Ishikawajima-Harmina Heavy Industries, Co, Ltd. (IHI), and the Nuclear Waste Department of Westinghouse Electric Corporation (WEC) are studying experiment concepts for obtaining data for the validation of geotechnical software. A general

approach for the data comparison process has been developed for use with large scale tests that allows an objective determination to be made of the confidence levels associated with the software.
Notes: He has some very good ideas on validation methodology. Although some of the terminology is different than DMSO, the fundamental ideas are good.

Reference Type: Journal Article
Author: Leijnse, Anton; Hassanizadeh, S. Majid
Year: 1994
Title: Model Definition and Model Validation
Journal: Advances in Water Resources
Volume: 17
Pages: 197-200
Abstract: In recent decades, groundwater models have been used in studying more and more complicated situations. The advanced users of groundwater models are in the framework of studies of groundwater contamination, nuclear/hazardous waste disposal, thermal energy storage/exploration, etc. In these applications, large temporal and/or spatial scales are often encountered and many uncertainties enter the model. As a result, the investigation of the validity of a model becomes a very complicated task and the issue of model validation takes a much greater dimension than that commonly associated with groundwater supply problems. Much discussion about validation of geo-hydrological models has taken place in recent years and, as might be expected, the opinions are diverse. A list of various studies on model validation is found in Tsang.
Notes: Gives a good distinction between models used for analysis versus prediction. He gives a very good list of references concerning validation in ground water models.

Reference Type: Book
Author: Lewis, Robert O.
Year: 1992
Title: Independent Verification and Validation
Publisher: John Wiley & Sons, Inc.
City: New York
Edition: 1st
Abstract: Part I. Compendium of Independent Verification and Validation Concepts
Part II. An Anthology of Independent Verification and Validation Disciplines: The Detailed How-To-Do-It Guide
Part III. A Guide to Planning and Applying Independent Verification and Validation
Part IV. Case Studies in Independent Verification and Validation
Notes: Very good reference on software V&V with the emphasis on "independent".

Reference Type: Journal Article
Author: Lin, S. J.; Barson, S. L.; Sindir, M. M.
Year: 1992
Title: Development of Evaluation Criteria and a Procedure for Assessing Predictive Capability and Code Performance

Pages: 11
Abstract: Computational fluid dynamics (CFD), because of its unique ability to predict complex three-dimensional flows is being applied within the industry. Such a procedure is needed to increase confidence in CFD and reduce risk in the use of these codes as a design and analysis tool. This paper defines classifications for three levels of code validation, directly relating the use of CFD codes to the engineering design cycle. Evaluation criteria by which codes are measured and classified are discussed. Criteria for experiments against which CFD results can be compared are outlined. A four phase CFD code validation procedure is described. Finally, the code validation procedure is demonstrated.
Notes: Good comments on practical application of validation in industry.

Reference Type: Conference Proceedings
Author: Ljung, L.; Guo, L.
Year: 1995
Title: Estimating the Total Model Error from a Standard Validation Test
Conference Name: 34th Conference on Decision & Control
Publisher: IEEE
Conference Location: New Orleans, LA
Pages: 1651-1656
Abstract: The problem of assessing the quality of a given, or estimated model is a central issue in system identification. Various new techniques for estimating bias and variance contributions to the model error have been suggested in the recent literature. In this contribution, classical model validation procedures are placed at the focus of our attention. We discuss the principles by which we reach confidence in a model through such validation techniques, and also how the distance to a "true" description can be estimated this way. In particular we stress how the typical model validation procedure gives a direct measure of the model error of the model test, without referring to its ensemble properties. Several model error bounds are developed for various assumptions about the disturbances entering the system.

Reference Type: Conference Proceedings
Author: Mair, Hans U.
Year: 1996
Title: Preliminary Compilation of Underwater Explosion Benchmarks
Conference Name: 67th Shock and Vibration Symposium
Publisher: SAVIAC
Volume: 1
Pages: 361-379
Abstract: An unclassified compilation of underwater explosion (UNDEX) benchmarks is presented in the interest of initiating a dialog within the UNDEX community on validation techniques. The compilation is preliminary; some information is incomplete, only minimal detail is provided, and the focus is limited to the response of submerged structures to underwater explosions. Both analytical and empirical benchmarks are presented. Each type has advantages and disadvantages for the purposes of model validation, though no methodology for employing these benchmarks in a model validation effort is proposed. A list of benchmark simulations known to the author is also compiled. Finally, extension of this compilation to the

Reference Type: Edited Book
Editor: Marciniak, J. J.
Year: 1994
Title: Encyclopedia of Software Engineering
Publisher: Wiley
City: New York
Notes: Good modern reference for software V&V.

Reference Type: Conference Proceedings
Author: Martellucci, A.
Year: 1990
Title: The Challenging Process of Validating CFD Codes
Conference Name: AIAA 16th Aerodynamic Ground Testing Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Seattle, WA
Volume: AIAA-90-1402
Pages: 12
Abstract: Computational fluid dynamics (CFD) has become the principal tool for the aerothermal design of vehicles for supersonic-hypersonic flight. Reliance on CFD for flight prediction is dictated by the inability of ground test facilities to provide the full simultaneous simulation of all pertinent hypersonic flows scaling parameters. While flight test provides the proper simulation, the measurement of key parameters required for CFD validation is difficult to achieve and is also extremely costly. This dictates that the CFD computer code formulations used for vehicle design must be technically sound, practical, and cost effective for use. The validation of these capabilities is a multi-step process proceeding from the basic general functioning of the code proceeding to the detailed examination and validation of the key submodules. In principle, validation is a continuous never ending process.

Reference Type: Conference Proceedings
Author: Marvin, J. G.
Year: 1988
Title: Accuracy Requirements and Benchmark Experiments for CFD Validation
Conference Name: Validation of Computational Fluid Dynamics
Publisher: AGARD
Conference Location: Lisbon, Portugal
Volume: AGARD-CP-437
Notes: Has some early ideas about validation experiments

Reference Type: Conference Proceedings
Author: Marvin, J. G.
Year: 1992

Title: A CFD Validation Roadmap for Hypersonic Flows
Conference Name: 70th Fluid Dynamics Panel Meeting and Symposium on Theoretical and Experimental Methods in Hypersonic Flows
Publisher: NATO Advisory Group for Aerospace Research & Development
Conference Location: Torino, Italy
Abstract: A roadmap for CFD code validation is developed. The elements of the roadmap are consistent with air-breathing vehicle design requirements and related to the important flow path components: forebody, inlet, combustor, and nozzle. Building block and benchmark validation experiments are identified along with their test conditions and measurements. Based on evaluation criteria, recommendations for an initial CFD validation data base are given and gaps identified where future experiments would provide the needed validation data.

Reference Type: Journal Article
Author: Marvin, Joseph G.
Year: 1995
Title: Perspective on Computational Fluid Dynamics Validation
Journal: AIAA Journal
Volume: 33
Issue: 10
Pages: 1778-1787
Abstract: A comprehensive to computational fluid dynamics (CFD) validation is presented. Requirements from computational and experimental perspectives are given. Experimental validation is emphasized because it ultimately determines the accuracy of CFD modeling and its application to complex problems. The concepts of building block and benchmark experiments are introduced. The types of measurements required of these experiments and their accuracy determination are explained. Contributions from such experiments toward the development and validation of CFD are reviewed and examples provided. Future challenges and strategies for validation are discussed.
Notes: He stresses the importance of code calibration.

Reference Type: Report
Author: McDonald, William W.
Year: 1995
Title: Introduction to the Submarine Damage Mechanisms Project
Institution: Naval Surface Warfare Center
Date: September 30, 1995
Report Number: IHTR 1824
Abstract: This report describes a statistical methodology that forms a key part of an interdisciplinary approach to damage prediction. The principal problem addressed is that of predicting submarine hull rupture caused by an underwater explosion. The statistical approach is compared with two other current approaches to the problem. The statistical approach is shown to be a synthesis and extension of these more deterministic alternatives. The report discusses the role of deterministic physical models in response prediction and how powerful deterministic computer codes can be utilized in constructing probability models for dependent, multivariate damage responses of interest. It describes how the statistical approach provides an

essential framework within which issues such as prediction accuracy, model validation, and decision making can be qualitatively and objectively addressed.
Notes: Good discussion of fluid-structure interaction during blast loading.

Reference Type: Conference Proceedings
Author: McIntyre, J.; Sicilian, J.; Giezen, J.
Year: 1990
Title: Benchmark Test Cases for Computational Fluid Dynamics
Conference Name: 1990 Spring Meeting of the Fluids Engineering Division
Editor: Celik, I.; Freitas, C. J.
Publisher: The American Society of Mechanical Engineers
Conference Location: Toronto, Ontario, CANADA
Volume: FED-Vol. 93
Pages: 38-47
Abstract: The calculation of fluid flows in spinning systems has many important applications including geophysics, spin-stabilized spacecraft, and processing technologies. Although the applications of interest often involve additional complications, there is a need for simple benchmarks to establish confidence in the numerical algorithms. In this paper we define a simple benchmark situation that produces non-trivial flows and has a well established analytical solution.
One critical aspect of incompressible flow in spinning systems is the existence of inertial waves. These waves, which arise from restoring forces associated with angular momentum conservation, introduce complex responses to simple disturbances. The principal aim of these benchmarks is to establish the ability of a numerical procedure to cope with the influence of inertial waves.
The benchmark begins from a state of rigid body rotation about the axis of symmetry of an enclosed tank. An instantaneous change in the axis of rotation is applied to model rigid body notation at a small angle. Linearized solutions are presented for both spheroidal and cylindrical tanks. The analytic theory leads to complicated pressure and velocity fields that generate a time-dependent force moment on the rigid body containing the tank. Benchmark comparisons are to be made to the resulting force moments only. The analytic solution is exact for the linearized equations in the case of a spheroidal tank. The cylindrical tank solution is a truncated series expansion whose terms are rapidly decaying.
Notes: This is a good reference for verification solutions for unsteady flows

Reference Type: Report
Author: McKay, M. D.
Year: 1995
Title: Evaluating Prediction Uncertainty
Institution: Los Alamos National Labs.
Date: March 1995
Report Number: NUREG/CR-6311 LA-12915-MS
Abstract: The probability distribution of a model prediction is presented as a proper basis for evaluating the uncertainty in a model prediction that arises from uncertainty in input values. Determination of important model inputs and subsets of inputs is made through comparison of

the prediction distribution with conditional prediction probability distributions. Replicated Latin hypercube sampling and variance ratios are used in estimation of the distributions and in construction of importance indicators. The assumption of a linear relation between model output and inputs is not necessary for the indicators to be effective. A sequential methodology which includes an independent validation step is applied in two analysis applications to select subsets of input variables which are the dominant causes of uncertainty in the model predictions. Comparison with results from methods which assume linearity shows how those methods may fail. Finally, suggestions for treating structural uncertainty for submodels are presented.
Notes: The main emphasis is on input uncertainties to models. He also has a good discussion of structural uncertainty due to submodels.

Reference Type: Report
Author: Mehta, Unmeel B.
Year: 1990
Title: The Aerospace Plane Design Challenge: Credible Computational Fluid Dynamics Results
Institution: NASA
Date: December 1990
Report Number: TM 102887
Abstract: Computational fluid dynamics (CFD) is necessary in the design processes of all current aerospace plane programs. Single-stage-to-orbit (SSTO) aerospace planes with air-breathing supersonic combustion are going to be largely designed by means of CFD. The challenge of the aerospace plane design is to provide credible CFD results to work from, to assess the risk associated with the use of those results to work from, to assess the risk associated with the use of those results, and to certify CFD codes that produce credible results. To establish the credibility of CFD results used in design, the following topics are discussed: CFD validation vis-a-vis "measurable" fluid dynamics (MFD) validation; responsibility for credibility; credibility requirement; and a guide for establishing credibility. Quantification of CFD uncertainties helps to assess success risk and safety risks, and the development of CFD as a design tool requires code certification. This challenge is managed by "designing" the designers to use CFD effectively, by ensuring quality control, and by balancing the design process. For designing the designers, the following topics are discussed: how CFD design technology is developed; the reasons Japanese companies, by and large, produce goods of higher quality, and teaming can be brought together. Quality control for reducing the loss imparted to the society begins with the quality of the CFD results used in the design process, and balancing the design process means using a judicious balance of CFD and MFD.

Reference Type: Journal Article
Author: Mehta, U. B.
Year: 1996
Title: Guide to Credible Computer Simulations of Fluid Flows
Journal: Journal of Propulsion and Power
Volume: 12
Issue: 5
Pages: 940-948

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Abstract: The significance of computer simulations depends solely on their credibility. A user of computer products, simulations and software, expects that these products are credible for the intended use. Because no standards exist for fluid-flow simulations by which to establish this credibility, a guide is presented here. The credibility is established by conducting verification and validation of simulation models and certification of simulations and of simulation software. Verification assesses whether the problem is solved correctly and estimates the level of computational accuracy of simulations; validation determines whether the right problem is solved and assesses the level of the validity of the simulation model by estimating the degree to which simulations accurately represent reality. These processes are achieved by identifying the intended uses of the simulations and the sources of uncertainties in them and by conducting sensitivity - uncertainty analyses. Certification determines 1) whether a software in terms of its logic, conceptual and computational models, procedures, rules, and documentation and 2) whether the simulations derived from the software are in compliance with specified requirements.

Reference Type: Journal Article
Author: Mehta, Unmeel B.
Year: 1998
Title: Credible Computational Fluid Dynamics Simulations
Journal: AIAA Journal
Volume: 36
Issue: 5
Pages: 665-667
Abstract: This summary presents the motivation for the Special Section on the credibility of computational fluid dynamics (CFD) simulations, its objective, its background and context, its content, and its major conclusions. Verification and validation (V&V) are the processes for establishing the credibility of CFD simulations. Validation assesses whether correct things are performed, and verification assesses whether they are performed correctly. Various aspects of V&V are discussed. Progress is made in verification of simulation models. Considerable effort is needed for assessing the validity of simulated reality.
Notes: This gives some history of validation activities in AIAA

Reference Type: Journal Article
Author: Miser, Hugh J.
Year: 1993
Title: A Foundational Concept of Science Appropriate for Validation in Operational Research
Journal: European Journal of Operational Research
Volume: 66
Pages: 204-215
Abstract: The purpose of this paper is to set forth, on the basis of a selected portion of the literature, an outline of a concept of science that can serve as an appropriate foundation for considering the problems of validation. To this end, it considers desiderata appropriate for such a concept, craft aspects of scientific inquiry, objects of scientific work, an overview of scientific processes, social aspects of scientific work, and the relations of these subjects to Operational Research. Then the paper considers what validation means in this structure, both for science generally and for Operational Research in particular. The conclusion points to the

essential contribution that validation makes to the maturity of a science, and hence the need for OR workers to study it more thoroughly and systematically than they have in the past.
Notes: Has a very good discussion of the philosophy of science as it pertains to validation. Has an extensive discussion of how scientific models are constructed.

Reference Type: Journal Article
Author: Mittal, R.; Balachandar, S.
Year: 1995
Title: Effect of Three-Dimensionality on the Lift and Drag of Nominally Two-Dimensional Cylinders
Journal: Physics of Fluids
Volume: 7
Issue: 8
Pages: 1841-1865
Abstract: It has been known for some time that two-dimensional numerical simulations of flow over nominally two-dimensional bluff bodies at Reynolds numbers for which the flow is intrinsically three dimensional, lead to inaccurate prediction of the lift and drag forces. In particular for flow past a normal flat plate (International Symposium on Nonsteady Fluid Dynamics, edited by J. A. Miller and D. P. Telionis, 1990, pp. 455-464) and circular cylinders (J. Wind Eng. Indus. Aerodyn. 35, 275 1990), it has been noted that the drag coefficient computed from two-dimensional simulations is significantly higher than what is obtained from experiments. Furthermore, it has been found that three-dimensional simulations of flows lead to accurate prediction of drag. The underlying cause for this discrepancy is that the surface pressure distribution obtained from two-dimensional simulations does not match up with that obtained from experiments and three-dimensional simulations and a number of reasons have been put forward to explain this discrepancy. However, the details of the physical mechanisms that ultimately lead to the inaccurate prediction of surface pressure and consequently the lift and drag, are still not clear. In the present study, results of two-dimensional and three-dimensional simulations of flow past elliptic and circular cylinders have been systematically compared in an effort to pinpoint the exact cause for the inaccurate prediction of the lift and drag by two-dimensional simulations. The overprediction of mean drag force in two-dimensional simulations is directly traced to higher Reynolds stresses in the wake. It is also found that the discrepancy in the drag between two-dimensional and three-dimensional simulations is more pronounced for bluffer cylinders. Finally, the current study also provides a detailed view of how the fluctuations, which are associated with the Karman vortex shedding in the wake, affect the mean pressure distribution and the aerodynamic forces on the body.
Notes: Good paper for CFD verification.

Reference Type: Book
Author: Morrison, Foster
Year: 1991
Title: The Art of Modeling Dynamic Systems Forecasting for Chaos, Randomness, and Determinism
Publisher: John Wiley & Sons, Inc.
City: New York

N

Edition: 1st
Abstract: Ch. 1 Introduction to Dynamics
Ch. 2 A Brief History of Dynamics and Computing
Ch. 3 Foundations and Abstract Entities
Ch. 4 Classical Analysis
Ch. 5 Numerical Analysis and Approximation Theory
Ch. 6 Statistical Methods
Ch. 7 Classical Modeling Techniques
Ch. 8 Dynamics without Calculus
Ch. 9 Basic Models
Ch. 10 Cycles
Ch. 11 Analysis of Mathematical Models
Ch. 12 A Classification Scheme for Dynamic Systems
Ch. 13 Static Systems - Type Zero
Ch. 14 Solvable Systems - Type I
Ch. 15 Perturbation Theory - Type II
Ch. 16 Chaotic Systems - Type III
Ch. 17 Stochastic Systems - Type IV
Ch. 18 Qualitative Analysis
Ch. 19 Quantitative Analysis
Ch. 20 Model Validation
Notes: Has a very nice mix of dynamics, ordinary differential equations, probability and statistics and nonlinear dynamical systems.

Reference Type: Report
Author: NASA
Year: 1995
Title: Formal Methods Specification and Verification Guidebook for Software and Computer Systems: Volume I, Planning and Technology Insertion
Institution: National Aeronautics and Space Administration
Date: July 1995
Report Number: NASA-GB-002-95; available: http://eis.jpl.nasa.gov/quality/Formal_Methods/
Abstract: Formal Methods (FM) consist of a set of techniques and tools based on mathematical modeling and formal logic that are used to specify and verify requirements and designs for computer systems and software. The use of FM on a project can assume various forms, ranging from occasional mathematical notation embedded in English specifications, to fully formal specifications using specification languages with a precise semantics. At their most rigorous, FM involve computer-assisted proofs of key properties regarding the behavior of the system. Project managers choose from this spectrum of FM options as appropriate to optimize the costs and benefits of FM use and to achieve a level of verification that meets the customer's needs and budget constraints. Experience suggests that these choices are most successful if based on certain managerial and technical considerations, which are the major focus of the guidebook. FM play an important role in many activities including certification, reuse, and assurance. Although the focus of this guidebook is restricted to the role of FM in requirements analysis, much of the discussion is also relevant to these other activities.

Notes: Good modern reference for formal methods in verification.

Reference Type: Report
Author: NASA
Year: 1997
Title: Formal Methods Specification and Verification Guidebook for Software and Computer Systems: Volume II, A Practitioner's Companion
Institution: National Aeronautics and Space Administration
Date: May 1997
Report Number: NASA-GB-001-97; available: http://eis.jpl.nasa.gov/quality/Formal_Methods/
Abstract: This volume presents technical issues involved in applying mathematical techniques known as Formal Methods to specify and analytically verify aerospace and avionics software systems. The first volume in this two-part series, NASA-GB-002-95 [NASA-95a], dealt with planning and technology insertion. This second volume discusses practical techniques and strategies for verifying requirements and high-level designs for software intensive systems. The discussion is illustrated with a realistic example based on NASA's Simplified Aid for EVA (Extravehicular Activity) Rescue [SAFER94a, SAFER94b]. The volume is intended as a "companion" and guide for the novice formal methods and analytical verification practitioner. Together, the two volumes address the recognized need for new technologies and improved techniques to meet the demands inherent in developing increasingly complex and autonomous systems. The support of NASA's Safety and Mission Quality Office for the investigation of formal methods and analytical verification techniques reflects the growing practicality of these approaches for enhancing the quality of aerospace and avionics applications.
Notes: Good modern reference for formal methods in verification.

Reference Type: Journal Article
Author: Naylor, Thomas H.; Finger, J. M.
Year: 1967
Title: Verification of Computer Simulation Models
Journal: Management Science
Volume: 14
Issue: 2
Pages: 92-101
Abstract: The problem of validating computer simulation models of industrial systems has received only limited attention in the management science literature. The purpose of this paper is to consider the problem of validating computer models in the light of contemporary thought in the fields of philosophy of science, economic theory, and statistics. In order to achieve this goal we have attempted to gather together and present some of the ideas of scientific philosophers, economists, statisticians, and practitioners in the field of simulation which are relevant to the problem of verifying simulation models. We have paid particular attention to the writings of economists who have been concerned with testing the validity of economic models. Among the questions which we shall consider are included: What does it mean to verify a computer model of an industrial system? Are there any differences between the verification of computer models and the verification of other types of models? If so, what are some of these differences? Also considered are a number of measures and techniques for testing the

"goodness of fit" of time series generated by computer models to observed historical series.
Notes: Gives a very good philosophy of science viewpoint of the issues in verification and validation. This is the paper that firmed up the modern DMSO definitions of verification and validation.

Reference Type: Book
Author: Neelamkavil, Francis
Year: 1987
Title: Computer Simulation and Modelling
Publisher: John Wiley & Sons
City: New York
Edition: 1st
Abstract: Ch. 1 Introduction and Overview
Ch. 2 Systems
Ch. 3 Models
Ch. 4 Model Validation
Ch. 5 Basic Probability and Statistics
Ch. 6 Random Numbers and Random Variates
Ch. 7 Discrete System Simulation
Ch. 8 General-purpose Simulation System (GPSS)
Ch. 9 SIMSCRIPT
Ch. 10 Simulation Experiments in Practice
Ch. 11 Continuous System Simulation
Ch. 12 Trends in Simulation
Notes: Very good introduction to fundamental system modeling, ordinary differential equations, and validation.

Reference Type: Journal Article
Author: Nishida, H.; Satofuka, N.
Year: 1992
Title: Higher-Order Solutions of Square Driven Cavity Flow Using a Variable-Order Multi-Grid Method
Journal: International Journal for Numerical Methods in Engineering
Volume: 34
Issue: 2
Pages: 637-653
Abstract: A new higher-order method is devised for the numerical simulation of square driven cavity flows. The spatial derivatives of the Navier-Stokes equations are discretized by means of the modified differential quadrature (MDQ) method. The resulting system of ordinary differential equations (ODEs) in time is then integrated by the classical fourth-order Runge-Kutta-Gill (RKG) scheme. The elliptic (Poisson) equation is solved by means of a new variable-order of accuracy up to 10th order. The results suggest that the higher order solutions are more reliable than the well-known results obtained by Ghia et al.
Notes: Good paper for CFD verification.

Reference Type: Report
Author: NRC
Year: 1997
Title: Regulatory Guide 1.168: Verification, Validation, Reviews, and Audits for Digital Computer Software Used in Safety Systems of Nuclear Power Plants
Institution: US Nuclear Regulatory Commission
Date: September 1997
Report Number: Available: www.nrc.gov/NRC/RG/01/01-168.htmt
Abstract: The use of industry consensus standards is part of an overall approach to meeting the requirements of 10 CFR Part 50 when developing safety systems for nuclear power plants. Compliance with standards does not guarantee that regulatory requirements will be met. However, compliance does ensure that practices accepted within various technical communities will be incorporated into the development and quality assurance processes used to design safety systems. These practices are based on experience, and they represent industry consensus on approaches used for development of such systems.
Software incorporated into instrumentation and control systems covered by Appendix B will be referred to in this regulatory guide as safety system software. For safety system software, software verification and validation (V&V), reviews, and audits are important parts of the effort to achieve compliance with the NRC's requirements. Software engineering practices rely, in part, on software V&V and on technical reviews and audits to meet general quality and reliability requirements consistent with Criteria 1 and 21 of Appendix A to 10 CFR Part 50, as well as Criteria II, III, XI, and XVIII of Appendix B. In addition, management reviews and audits of software processes are part of a verification process consistent with Criterion I of Appendix B.
Notes: Deals with software quality assurance.

Reference Type: Conference Proceedings
Author: Oberkampf, William L.
Year: 1994
Title: A Proposed Framework for Computational Fluid Dynamics Code Calibration/Validation
Conference Name: 18th AIAA Aerospace Ground Testing Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Colorado Springs, CO
Volume: AIAA Paper No. 94-2540
Abstract: The paper reviews the terminology and methodology that have been introduced during the last several years for building confidence in the predictions from Computational Fluid Dynamics (CFD) codes. Code validation terminology developed for nuclear reactor analyses and aerospace applications is reviewed and evaluated. Currently used terminology such as "calibrated code", "validated code," and "validation experiment" is discussed along with the shortcomings and criticisms of these terms. A new framework is proposed for building confidence in CFD code predictions that overcomes some of the difficulties of past procedures and delineates the causes of uncertainty in CFD predictions. Building on previous work, new definitions of code verification and calibration are proposed. These definitions provide more specific requirements for the knowledge level of the flow physics involved and the solution accuracy of the given partial differential equations. As part of the proposed framework, categories are also proposed for flow physics research, flow modeling research,

and the application of numerical predictions. The contributions of physical experiments, analytical solutions, and other numerical solutions are discussed, showing that each should be designed to achieve a distinctively separate purpose in building confidence in accuracy of CFD predictions. A number of examples are given for each approach to suggest methods for obtaining the highest value for CFD code quality assurance.
Notes: Reviews the literature in V&V and presents some ideas for a possible framework for verification and validation.

Reference Type: Journal Article
Author: Oberkampf, W. L.; Aeschliman, D. P.
Year: 1992
Title: Joint Computational/Experimental Aerodynamics Research on a Hypersonic Vehicle: Part 1, Experimental Results
Journal: AIAA Journal
Volume: 30
Issue: 8
Pages: 2000-2009
Abstract: Aerodynamic force and moment measurements and flow visualization results are presented for a hypersonic vehicle configuration at Mach 8. All of the experimental results were obtained in the Sandia National Laboratories Mach 8 hypersonic wind tunnel for laminar boundary-layer conditions. The basic vehicle configuration is a spherically blunted 10-deg half-angle cone with a slice parallel with the axis of the vehicle. On the slice portion of the vehicle, a flap can be attached so that deflection angles of 10, 20, and 30 deg can be obtained. Surface flow visualization showed separated flow in front of each flap configuration. A detailed uncertainty analysis was conducted to estimate the contributors to body force and moment measurement uncertainty. In this paper, comparisons are made with computational results to evaluate both the experimental and numerical results. This extensive set of high-quality experimental force and moment measurements is recommended for use in the calibration and validation of relevant computational aerodynamics codes.
Notes: Describes a CFD validation experiment and gives experimental data for validation.

Reference Type: Conference Proceedings
Author: Oberkampf, W. L.; Aeschliman, D. P.; Henfling, J. F.; Larson, D. E.
Year: 1995
Title: Surface Pressure Measurements for CFD Code Validation in Hypersonic Flow
Conference Name: 26th Fluid Dynamics Conf.
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: San Diego, CA
Volume: AIAA Paper No. 95-2273
Abstract: Extensive surface pressure measurements were obtained on a hypersonic vehicle configuration at Mach 8. All of the experimental results were obtained in the Sandia National Laboratories Mach 8 hypersonic wind tunnel for laminar boundary layer conditions. The basic vehicle configuration is a spherically blunted 10 degree half-angle cone with a slice parallel with the axis of the vehicle. The bluntness ratio of the geometry is 10% and the slice begins at 70% of the length of the vehicle. Surface pressure measurements were obtained for angles of

attack from -10 to +18 degrees, for various roll angles, at 96 locations on the body surface. A new and innovative uncertainty analysis was devised to estimate the contributors to surface pressure measurement uncertainty. Quantitative estimates were computed for the uncertainty contributions due to the complete instrumentation system, nonuniformity of flow in the test section of the wind tunnel, and variations in the wind tunnel model. This extensive set of high-quality surface pressure measurements is recommended for use in the calibration and validation of computational fluid dynamics codes for hypersonic flow conditions.
Notes: Gives experimental data for CFD validation.

Reference Type: Conference Proceedings
Author: Oberkampf, W. L.; Aeschliman, D. P.; Henfling, J. F.; Larson, D. E.; Payne, J. L.
Year: 1996
Title: Surface Pressure Measurements on a Hypersonic Vehicle
Conference Name: 34th Aerospace Sciences Meeting
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Reno, NV
Volume: AIAA Paper No. 96-0669
Abstract: Extensive surface pressure measurements were obtained on a hypersonic vehicle configuration at Mach 8 for the purpose of computational fluid dynamic code validation. Experiments were conducted in the Sandia National Laboratories hypersonic wind tunnel. All measurements were made for laminar flow conditions at a Reynolds number (based on model length) of 1.81×10^6 and perfect gas conditions. The basic vehicle configuration is a spherically blunted, 10 deg. half-angle cone, with a slice parallel to the axis of the vehicle. Flaps of varying angle (10, 20, and 30 deg) could be attached to the aft portion of the slice. Surface pressure measurements at 96 locations on the body surface were obtained for angles of attack from -10 to +18 deg and for various roll angles. All three deflected flap angles produced separated flow on the sliced portion of the body in front of the flap. Because of the three-dimensional expansion over the slice, the separated flow on the slice and flap was highly three-dimensional. The results of the present experiment provide extensive surface pressure measurements for the validation of computational fluid dynamics codes for separated flow caused by an embedded shock wave.
Notes: Gives experimental data for CFD validation.

Reference Type: Report
Author: Oberkampf, William L.; Blottner, Frederick G.
Year: 1997
Title: Issues in Computational Fluid Dynamics Code Verification and Validation
Institution: Sandia National Labs.
Date: Sept. 1997
Report Number: SAND95-1352
Abstract: A broad range of mathematical modeling errors of fluid flow physics and numerical approximation errors are addressed in computational fluid dynamics (CFD). It is strongly believed that if CFD is to have a major impact on the design of engineering hardware and flight systems, the level of confidence in complex simulations must substantially improve. To better

understand the present limitations of CFD simulations, a wide variety of physical modeling, discretization, and solution errors are identified and discussed. Here, discretization and solution errors refer to all errors caused by conversion of the original partial differential, or integral, conservation equations representing the physical process, to algebraic equations and their solution on a computer. The impact of boundary conditions on the solution of the partial differential equations and their discrete representation will also be discussed. Throughout the article, clear distinctions are made between the analytical mathematical models of fluid dynamics and the numerical models. Lax's Equivalence Theorem and its frailties in practical CFD solutions are pointed out. Distinctions are also made between the existence and uniqueness of solutions to the partial differential equations as opposed to the discrete equations. Two techniques are briefly discussed for the detection and quantification of certain types of discretization and grid resolution errors.
Notes: Discusses methodology for CFD verification and validation and points out some problem areas.

Reference Type: Journal Article
Author: Oberkampf, William L.; Blottner, Frederick G.
Year: 1998
Title: Issues in Computational Fluid Dynamics Code Verification and Validation
Journal: AIAA Journal
Volume: 36
Issue: 5
Pages: 687-695
Abstract: A broad range of mathematical modeling errors of fluid flow physics and numerical approximation errors is addressed in computational fluid dynamics (CFD). It is strongly believed that, if CFD is to have a major impact on the design of engineering hardware and flight systems, the level of confidence in complex simulations must substantially improve. To better understand the present limitations of CFD simulations, a wide variety of physical modeling, discretization, and solution errors are identified and discussed. Here, discretization and solution errors refer to all errors caused by conversion of the original partial differential, or integral, conservation equations representing the physical process to algebraic equations and their solution on a computer. The impact of boundary conditions on the solution of the partial differential equations and their discrete representation are discussed. Clear distinctions are made between the analytical mathematical models of fluid dynamics and the numerical models. Lax's Equivalence Theorem and its frailties in practical CFD Solutions are pointed out. Distinctions are also made between the existence and uniqueness of solutions to the partial differential equations as opposed to the discrete equations. Two techniques for the detection and quantification of certain types of discretization and grid resolution errors are briefly discussed.
Notes: Discusses methodology for CFD verification and validation and points out some problem areas.

Reference Type: Journal Article
Author: Oral, Muhittin; Kettani, Ossama
Year: 1993

Title: The Facets of the Modeling and Validation Process in Operations Research
Journal: European Journal of Operational Research
Volume: 66
Pages: 216-234
Abstract: The present paper suggests a way of exploring the process of modeling and validation in Operations Research (OR). This will be achieved by providing an interpretation for each facet of the modeling-validation tetrahedron formed by the quartet 'managerial situation', 'conceptual model', 'formal model', and 'decision'. Such an approach not only leads to a contextual classification of OR problems, albeit in general terms, but also helps to identify the types of validation needed and their relative importance. The real world problems which OR is currently trying to tackle are rather complex in nature and vast in scope. This inevitably forces OR scientists and practitioners to position themselves somewhere on the 'scientific perspective' - 'practice perspective' spectrum. The proposed tetrahedron of the modelling - validation process is also instrumental in positioning OR workers with respect to the nature of their work.
Notes: Authors suggest a tetrahedron to describe the OR modeling and simulation process.

Reference Type: Journal Article
Author: Oren, Tuncer I.
Year: 1981
Title: Concepts and Criteria to Assess Acceptability of Simulation Studies: A Frame of Reference
Journal: Communications of the ACM
Volume: 24
Issue: 4
Pages: 180-189
Abstract: The existing trend of application of computerized simulation studies to large and complex systems necessitates the development of an assessment methodology for simulation studies. The basic concepts and criteria necessary for such an assessment methodology are presented in a systematic way. The proposed framework permits discussion of the concepts and criteria related to the acceptability of the following components of a simulation study: Simulation results, real world and simulated data, parametric model and the values of the model parameters, specification of the experimentation, representation and execution of the computer program, and modeling, experimentation, simulation, and programming methodologies or techniques used. The acceptability of the components of a simulation study are discussed with respect to the goal of the simulation study, the structure and data of the real system, the parametric model, the model parameter set, the specification of the experimentation, and the existing or conceivable norms of modeling methodology, experimentation technique, simulation methodology, and software engineering.
Notes: He has some very good insights into the early understanding of verification and validation methodology.

Reference Type: Edited Book
Editor: Oren, Tuncer I.; Zeigler, Bernard P.; Elzas, Maurice S.
Year: 1984
Title: Simulation and Model-Based Methodologies: An Integrative View

O

Publisher: Springer-Verlag Berlin Heidelberg
Abstract: Sec. 1 Conceptual Bases for System Modelling and Design
1 Model-Based Activities: A Paradigm Shift-Tuncer I. Oren
2 System Paradigms as Reality Mappings-Maurice S. Elzas
3 General Systems Framework for Inductive Modelling-George J. Klir
4 System Theoretic Foundations of Modelling and Simulation-Bernard P. Zeigler
5 The Tricotyledon Theory of System Design-A. Wayne Wymore
6 Concepts for Model-Based Policy Construction-Maurice S. Elzas
Sec. 2 Model-Based Simulation Architecture
7 Structures for Model-Based Simulation Systems-Bernard P. Zeigler
8 Symbolic Manipulation of System Models-Franz Pichler
9 Concepts for an Advanced Parallel Simulation Architecture-Len Dekker
Sec. 3 Impact of Formalisms on Model Specification
10 GEST - A Modeling and Simulation Language Based on System Theoretic Concepts-Tuncer I. Oren
11 Continuous and Discontinuous-Change Models: Concepts for Simulation Languages-Roy E. Crosbie
12 Discrete Event Formalism and Simulation Model Development -Sudhir Aggarwal
Sec. 4 Model Identification, Reconstruction, and Optimization
13 Structure Characterization for Ill-Defined Systems-Jan A. Spriet and Ghislain C. Vansteenkiste
14 Reconstructability Analysis: An Overview-George J. Klir
15 SAPS-A Software System for Inductive Modeling-Hugo J. J. Uyttenhove
16 Optimization in Simulation Studies-Louis G. Birta
Sec. 5 Quality Assurance in Model-Based Activities
17 Quality Assurance in Modeling and Simulation: A Taxonomy-Tuncer I. Oren
18 How to Enhance the Robustness of Simulation Software-Francois E. Cellier
19 Simulation Model Validation-Robert G. Sargent
20 Critical Issues in Evaluating Socio-Economic Models-John Henize
Sec. 6 Contributed Workshop Presentations
Group 1 Model Based Simulation Architecture
Group 2 Impact of Formalisms on Model Specification
Group 3 Model Identification, Reconstruction, and Optimization
Group 4 Quality Assurance in Model-Based Activities

Reference Type: Magazine Article
Author: Oreskes, Naomi; Shrader-Frechette, Kristin; Belitz, Kenneth
Year: 1994
Title: Verification, Validation, and Confirmation of Numerical Models in the Earth Sciences
Magazine: Science
Volume: 263
Pages: 641-646
Date: February 4, 1994
Abstract: Verification and validation of numerical models of natural systems is impossible. This is because natural systems are never closed and because model results are always non-unique. Models can be confirmed by the demonstration of agreement between observation and

prediction, but confirmation is inherently partial. Complete confirmation is logically precluded by the fallacy of affirming the consequent and by incomplete access to natural phenomena. Models can only be evaluated in relative terms, and their predictive value is always open to question. The primary value of models is heuristic.
Notes: The authors take a very purist view of verification and validation. Although they make some good points about the inability to "prove" any model, consistent with Karl Popper, they get bogged down in the issue of “truth,” instead of confidence in simulations.

Reference Type: Conference Proceedings
Author: Pace, Dale K.
Year: 1997
Title: Fidelity Considerations for RDE Distributed Simulation
Conference Name: 1997 Fall Simulation Interoperability Workshop Papers
Volume: 1
Pages: 249-259
Abstract: Research, development, and engineering (RDE) distributed simulations may be used to support decisions about system design and effectiveness. Accuracy and precision of experiment and test data related to the system, fidelity of simulation results, correctness of simulation input data, and dispersion of real system performance all must be addressed acceptably so that system decisions can account for performance risks appropriately. This can be a significant problem for systems with stringent performance requirements. These fidelity considerations are not peculiar to distributed simulation, but become more complicated in a distributed simulation environment (especially one which includes both live and constructive forces) because fidelity of simulation results is a consequence of the appropriateness of algorithms employed, implementation limitations imposed by hardware or personnel, and the impact of the distributed simulation environment on fidelity. This paper provides a construct for addressing these issues and identifies an approach to developing more robust methodologies to deal with these issues than is presently employed. Examples to illustrate the importance of this subject are drawn from experiment, test, and simulation related to theater missile defense systems.
Notes: This article is very good on the elements that affect the quantification of validation in modeling and simulation.

Reference Type: Conference Proceedings
Author: Pace, Dale K.
Year: 1998
Title: Dimensions and Attributes of Simulation Fidelity
Conference Name: 1998 Fall Simulation Interoperability Workshop Papers
Volume: 1
Pages: 9
Abstract: Simulation fidelity is tenebrous. Varied and sometimes conflicting ideas about simulation fidelity exist. Part of the current confusion stems from failure to distinguish between the dimensions and attributes of simulation fidelity; the dimensions of fidelity indicate the extent to which significant elements of the subject domain (mission space) are treated by the simulation and the fidelity attributes indicate the quality of treatment for significant factors

addressed by the simulation. In addition, part of the confusion about simulation fidelity stems from mixing qualitative ideas with quantitative concepts. The paper strives to bring clarity to discussion of simulation fidelity by distinguishing the dimensions of fidelity from the attributes of fidelity and by keeping qualitative ideas about fidelity distinct from quantitative concepts. In so doing, it provides a foundation upon which more comprehensive frameworks for simulation fidelity can be developed. This approach does not permit a description of simulation fidelity by a single parameter, but requires a collection of parameters to describe simulation fidelity. Concepts in this paper draw heavily upon the simulation fidelity literature, both that published within the distributed simulation community and that published elsewhere. As far as possible, terminology in the paper is consistent with terms in the short glossary of fidelity related terms published at the 1997 Spring SIW by the Fidelity Subgroup of the Research, Development, and Engineering (RDE) User Community Forum.
Notes: Very good article dealing with quantification of validation

Reference Type: Conference Proceedings
Author: Pace, Dale K.
Year: 1998
Title: Synopsis of Fidelity Ideas and Issues
Conference Name: 1998 Spring Simulation Interoperatibility Workshop Papers
Volume: 1
Pages: 420-429
Abstract: This paper provides a synopsis of simulation fidelity ideas and issues, especially as they pertain to distributed simulation. The goal of this paper is to provide a solid information foundation from past endeavors to support continuing discussion of the important topic of simulation fidelity. The references of this appear identify not only previously published fidelity appears, reports, documents, and websites from various sources, including past Simulation Interoperability (SIW) and Distributed Interactive Simulation (DIS) workshops, but also identify the dozen fidelity related papers submitted for the March 1998 SIW. A brief comment about the January 1998 meeting of the Fidelity Subgroup of the SIW Research, Development, and Engineering (RDE) User Community Forum is included at the end of the paper. This paper should be a valuable resource for those who wish to take advantage of past thinking on fidelity issues.
Notes: Very good review of validation issues and a very good list of references

Reference Type: Book
Author: Pegden, C. Dennis; Shannon, Robert E.; Sadowski, Randall P.
Year: 1990
Title: Introduction to Simulation Using SIMAN
Publisher: McGraw-Hill, Inc.
City: New York
Edition: 1st
Abstract: Ch 1 Introduction to Modeling
Ch 2 Beginning the Study
Ch 3 Basic Modeling Concepts
Ch 4 Model Verification and Validation

Ch 5 Interpreting Simulation Output
Ch 6 Station Submodels and Entity Transfers
Ch 7 Animating the Simulation by Using Cinema
Ch 8 Additional Discrete Modeling Concepts
Ch 9 Advanced Manufacturing Features
Ch 10 Interfacing User-Written Subprograms
Ch 11 Continuous and Combined Models
Ch 12 Variance Reduction Techniques
Notes: Most of the book deals with discrete event simulation.

Reference Type: Book Section
Author: Plant, Robert T.
Year: 1993
Title: The Validation and Verification of Complex Knowledge-Based Systems
Book Title: Verification and Validation of Complex Systems: Human Factors Issues
Editor: Wise, John A.; Hopkin, V. David; Stager, Paul
Publisher: Springer-Verlag
City: Coral Gables, FL
Pages: 193-202
Abstract: The development of a knowledge-based system can be created through several alternative methodological approaches (see Buchanan et al., 1983; Grover, 1983; Alexander et al., 1986; Weitzel & Kershberg, 1989; Miller, 1990; Plant, 1992) which have been utilized to differing degrees of success. The aim of this paper is to consider one of these methodologies (Plant, 1992), and introduce a Validation and Verification Methodology to accompany the Development Methodology.
The area of knowledge-based system development has not until recently benefited from the adoption of unified methodologies; the previous methodologies were stage based in style and thus lacked a continuous refinement approach to system creation. This in turn induced difficulties in the validation and verification process. For the systems themselves were poorly defined and lacking in specifications, making validation impractical and verification a futile effort in hitting a moving target. The ultimate outcome has been the adoption of ad-hoc style developments based upon prototyping with weak, often case-based validation and verification, producing low quality and unreliable systems.

Reference Type: Conference Proceedings
Author: Porter, John L.
Year: 1996
Title: A Summary/Overview of Selected Computational Fluid Dynamics (CFD) Code Validation/Calibration Activities
Conference Name: 27th AIAA Fluid Dynamics Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: New Orleans, LA
Volume: AIAA Paper No. 96-2053
Pages: 11
Abstract: The results of a series of workshops sponsored by the Joint

Army/Navy/NASA/AirForce (JANNAF) Airbreathing Propulsion Committee are reviewed. The results address the need for, and the process needed for establishing, archival benchmark experiments; the definition of the validation process; the process of establishing CFD code validation/verification test programs; and information management for the CFD experimental archival data. The results are presented from the points of view of experimentalists, code developers, and generalists/managers. The issues associated with the validation process are also discussed and summarized. The coordination of the workshop activities with other organizations: AGARD, SAE, and the AIAA, is also described. Developments regarding publications standards being addressed by the AIAA CFD Committee on Standards (CFD/COS) are described. Key steps required to help CFD play a more viable role in engineering design and performance processes are discussed in the paper's summary.

Reference Type: Book
Author: Rakitin, Steven R.
Year: 1997
Title: Software Verification and Validation
Abstract: Part I: Introduction 1
Chapter 1 Software in perspective
Chapter 2 Software development lifecycle models
Chapter 3 The software development process
Chapter 4 Economic justification
Part II: Overview of Software verification activities
Chapter 5 The inspection process
Chapter 6 Applying the inspection process
Chapter 7 Software quality metrics
Chapter 8 Configuration management
Part III: Overview of Software Validation Activities
Chapter 9 Testing
Chapter 10 Software validation metrics
Chapter 11 Software reliability growth
Appendix A Inspection roles and responsibilities
Appendix B A sample inspection process
Appendix C Inspection process forms
Appendix D Inspection checklists
Appendix E Attributes of good requirements specifications
Appendix F Sample criteria for selecting modules for code inspection
Appendix G Sample software development process based on the waterfall model
Appendix H Document outlines
Appendix I Test cases for triangle program
Appendix J Software reliability models
Notes: This is a very good, modern book on software verification and validation

Reference Type: Journal Article
Author: Reed, Helen L.; Haynes, Tim S.; Saric, William S.
Year: 1998
Title: Computational Fluid Dynamics Validation Issues in Transition Modeling

Journal: AIAA Journal
Volume: 36
Issue: 5
Pages: 742-751
Abstract: Laminar-turbulent transition is highly initial- and operating-condition dependent. Finding careful, archival experiments for comparison is the main validation issue for computational fluid dynamics (CFD) modeling. The CFD formulations validated to date demonstrate that if the environment and operating conditions can be modeled and input correctly, the computations (nonlinear parabolized stability equations and direct numerical simulations) agree quantitatively with the experiments. Future challenges for validation include successful CFD simulations of other available complete databases, CFD leadership in the identification and modeling of the effects of freestream disturbances, CFD leadership in the determination of relevant validation experiments for supersonic and hypersonic flows, careful validation experiments and CFD solutions for complex three-dimensional geometries, and simulations and validations for the high Reynolds numbers of flight.

Reference Type: Conference Proceedings
Author: Rizzi, A.; Vos, J.
Year: 1996
Title: Towards Establishing Credibility in CFD Simulations
Conference Name: 27th AIAA Fluid Dynamics Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: New Orleans, LA
Volume: AIAA Paper No. 96-2029
Pages: 13
Abstract: The paper outlines essential steps towards establishing credibility in CFD simulations and suggests a vision for the process of systematic validation. It begins with an exposition of the elements of CFD simulations and defines protocols useful for establishing credibility. The various sources of uncertainty in CFD are presented, which includes a discussion of the skills of the user. Lessons learned from verification and validation exercises done in the past are reviewed and lead to our suggestion for a systematic validation process that requires the creation and use of a detailed flow taxonomy for the given application field. The code validator uses the taxonomy and an electronic database to carry out the validation process. This database archives, but also gives easy access to trustworthy data, and allows full public discussion and scrutiny of the information, comparisons and hypotheses in order that judgments and conclusions about the validation may be accepted or rejected. The taxonomy also is the basis upon which the code user transfers credibility from previously validated generic flow cases to the simulation at hand.

Reference Type: Journal Article
Author: Rizzi, Arthur; Vos, Jan
Year: 1998
Title: Toward Establishing Credibility in Computational Fluid Dynamics Simulations
Journal: AIAA Journal
Volume: 36

Issue: 5
Pages: 668-675
Abstract: Essential steps toward establishing credibility in computational fluid dynamics (CFD) simulations are outlined, and a vision for the process of systematic collaborative validation that is open to public scrutiny via the Internet is suggested. It begins with an exposition of the elements of CFD simulations and reviews protocols useful for establishing credibility. The various sources of uncertainty in CFD, which include the skills of the user, are presented. Lessons learned from collective verification and validation exercises done in the past are surveyed and lead to our suggestion for a systematic validation process that requires the creation and use of a detailed flow taxonomy and an electronic database to carry out the validation process. This database archives but also gives easy access to trustworthy data and allows full public discussion and scrutiny of the information, comparisons, and hypotheses so that judgments and conclusions about the validation may be accepted or rejected by the scientific community at large. The taxonomy also is the basis on which the code user transfers credibility from previously validated generic flow cases to the simulation at hand.

Reference Type: Book Section
Author: Roache, P. J.
Year: 1982
Title: Scaling of High-Reynolds-Number Weakly Separated Channel Flows
Book Title: Numerical Aspects of Physical Aspects of Aerodynamic Flows
Editor: Cebecci, T.
Publisher: Springer-Verlag
City: New York
Pages: 87-98
Notes: Good classic reference dealing with the application of Richardson extrapolation for verification solutions.

Reference Type: Journal Article
Author: Roache, P. J.
Year: 1990
Title: Need for Control of Numerical Accuracy
Journal: Journal of Spacecraft and Rockets
Volume: 27
Issue: 2
Pages: 98-102
Abstract: The need for the control of numerical accuracy in computational fluid dynamics (CFD) code solutions is reviewed in the light of current journal practice and experience with implementation of an editorial policy on the same subject published by the Journal of Fluids Engineering. Various actual objections to that policy are listed and responses are given. The general successes and particular difficulties experienced in the implementation of the policy are noted. The broader question of code verification, validation, and certification is considered. It is suggested that professional societies such as the AIAA and American Society of Mechanical Engineers may ultimately become involved in the task of certification of commercially available CFD codes.

Notes: His thoughts on coding verification are very good.

Reference Type: Conference Proceedings
Author: Roache, P. J.
Year: 1995
Title: Verification of Codes and Calculations
Conference Name: 26th AIAA Fluid Dynamics Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: San Diego, CA
Volume: AIAA Paper No. 95-2224
Pages: 13
Abstract: Background discussion, definitions and descriptions are given for some terms related to confidence-building in CFD. Examples are given of worthwhile semantics vs. worthless semantics, and practical definitions vs. conceptual modeling errors; iterative convergence vs. grid convergence (or residual "accuracy" vs. discretization accuracy); confirmation, calibration, tuning, and certification, verification of codes vs. verification of individual calculations; truncation error vs. discretization error; customer illusions vs. customer care; and Quality Assurance vs. quality work. Emphasis is given to rigorous code verification via systematic grid convergence, and a simple method for uniform reporting of grid convergence studies using the Grid Convergence Index (GCI). Also discussed are error taxonomies, error presentation via the Cumulative Area Fraction Error (CAFE) curves, and surrogate single-grid error indicators based on energy imbalance.
Notes: Has some very good comments on the terminology of verification of codes and calculations.

Reference Type: Book Section
Author: Roache, P. J.
Year: 1997
Title: Quantification of Uncertainty in Computational Fluid Dynamics
Book Title: Annual Review of Fluid Mechanics
Publisher: Annual Reviews, Inc.
Volume: 29
Pages: 126-160
Abstract: This review covers verification, validation, confirmation and related subjects for computational fluid dynamics (CFD), including error taxonomies, error estimation and banding, convergence rates, surrogate estimators, nonlinear dynamics, and error estimation for grid adaptation vs. quantification of uncertainty.
Notes: Very good review of verification methodology in CFD.

Reference Type: Book
Author: Roache, P. J.
Year: 1998
Title: Verification and Validation in Computational Science and Engineering
Publisher: Hermosa Publishers
City: Albuquerque, NM

Abstract: Ch. 1 Introduction
Ch. 2 Semantics; Terminology, Taxonomies, and Definitions
Ch. 3 A Methodology for Accuracy Verification of Codes: the Method of Manufactured Solutions
Ch. 4 Error Estimation for Quantification of Uncertainty; Verification of Calculations
Ch. 5 Systematic Grid Convergence Studies and the Grid Convergence Index (GCI)
Ch. 6 Applications of Systematic Grid Convergence Studies and the Grid Convergence Index
Ch. 7 Single Grid Error Estimators
Ch. 8 Hard Stories
Ch. 9 Difficulties With Experiments and Validation
Ch. 10 Methodologies and Examples of Validations, Calibrations, and Certifications
Ch. 11 Code Quality Assurance and Certification
Ch. 12 Conclusions
Notes: The most complete reference on verification and validation in computational simulation.

Reference Type: Journal Article
Author: Roache, Patrick J.
Year: 1998
Title: Verification of Codes and Calculations
Journal: AIAA Journal
Volume: 36
Issue: 5
Pages: 696-702
Abstract: Background discussion, definitions, and descriptions are given for some terms related to confidence building between verification of codes vs verification of individual calculations. Also discussed are numerical errors vs conceptual modeling errors; iterative convergence vs grid convergence (or residual accuracy vs discretization accuracy); confirmation, calibration, tuning, and certification; error taxonomies; and customer illusions vs customer care. Emphasis is given to rigorous code verification via systematic grid convergence using the method of manufactured solutions, and a simple method for uniform reporting of grid convergence studies using the Grid Convergence Index (GCI). Also discussed are surrogate single-grid error indicators.
Notes: Has some very good comments on terminology, particularly verification of codes versus verification of calculations.

Reference Type: Conference Proceedings
Author: Roache, P. J.; Knupp, P. M.; Steinberg, S.; Blaine, R. L.
Year: 1990
Title: Benchmark Test Cases for Computational Fluid Dynamics
Conference Name: 1990 Spring Meeting of the Fluids Engineering Division
Editor: Celik, I.; Freitas, C. J.
Publisher: The American Society of Mechanical Engineers
Conference Location: Toronto, Ontario, CANADA
Volume: FED-Vol. 93
Pages: 49-56

Abstract: Experience with formulating and applying several benchmark test cases in groundwater hydrology CFD problems is described. Three problem categories are considered: (1) full 2-D groundwater hydrology problem codes tested on a steady problem with scalar conductivities in stretched cartesian coordinates; (2) Fortran subroutines produced by computer Symbolic Manipulation for the stencil array evaluation of tensor conductivity in general non-orthogonal 2-D and 3-D coordinates; (3) particle tracking in 2-D and 3-D. Freedom from coding errors, consistency of the discretization, and order of convergence are verified. Examples are given of successful code verification, successful error detection, and unsuccessful "false negative" tests. The codes tested involve a commercial code (SWIFT II), two codes produced by USGS personnel (MODFLOW and HST3D), and our own codes (SECO, for Sandia-ECOdynamics).
Notes: Good comments about sources of errors; some due to the code, some due to the code user

Reference Type: Book
Author: Rook, P.
Year: 1990
Title: Software Reliability Handbook
Publisher: Elsevier Science Publishers
City: New York
Notes: Good modern reference for software V&V.

Reference Type: Book Section
Author: Rosness, Ragnar
Year: 1993
Title: Limits to Analysis and Verification
Book Title: Verification and Validation of Complex Systems: Human Factors Issues
Editor: Wise, John A.; Hopkin, V. David; Stager, Paul
Publisher: Springer-Verlag
City: Trondheim, Norway
Pages: 181-191
Abstract: The term 'complexity' covers a wide variety of system attributes in everyday language. It may refer to the number of subsystems or components, the dynamics of component or subsystems behavior, the number of possible interactions, the presence of non-linear interactions, difficulties in identifying and understanding a system's interactions with its environment, the impact of human judgment and actions, or even our lack of familiarity with the system. We will not give a rigorous definition of complexity here. A workable approximation may be to state that complexity is a function of the number and properties of the dependencies (intentional and unintentional) which exist between the items of a system and between a system and its environment (adapted from Mancini, 1988).

Reference Type: Personal Communication
Author: Rubbert, Paul E.
Year: 1996
Title: What CFD Code Validation/Verification is -- and isn't
Date: January 2, 1996

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Abstract: What Conventional Wisdom didn't Tell You.
Goal is not to make CFD as accurate as wind tunnels.
Goal is not to get CFD and wind tunnels to produce the same result.
Goal is not to create trust, but to generate distrust.
CFDrs should never be allowed to compare their results with experiment.
Validating CFD by use of archived experiments is impossible.

Reference Type: Book Section
Author: Sargent, R. G.
Year: 1982
Title: Verification and Validation of Simulation Models
Book Title: Progress in Modeling and Simulation
Editor: Cellier, Francois E.
Publisher: Academic Press
City: Syracuse
Pages: 159-168
Abstract: Simulation models are frequently used today to aid in decision-making and problem-solving. The users of information from such models are usually rightfully concerned with whether the models and the information being generated from them can be used with confidence. This concern is usually addressed by simulation model-builders in the simulation methodology steps of verification and validation (5, 14, 25, 32). Verification is usually defined as ensuring that the model behaves (runs) as intended, and validation is usually defined as determining that an adequate agreement exists between the entity being modelled and the model for its intended use (7, 14, 25, 28, 30). One must, however, be careful because thse words are used in a variety of ways (20, 27, 28). Our use of them will be as they are defined here.
Notes: This article is very good early article on V&V. An updated version of this paper appeared in the 1985 Winter Simulation Conference.

Reference Type: Book Section
Author: Sargent, Robert G.
Year: 1984
Title: Simulation Model Validation
Book Title: Simulation and Model-Based Methodologies: An Integrative View
Editor: Oren, Tuncer I.; Zeigler, Bernard P.; Elzas, Maurice S.
Publisher: Springer-Verlag Berlin Heidelberg
City: Syracuse
Pages: 537-555
Abstract: The subject of this chapter is model validation which is defined to mean "substantiation that a computerized model within its domain of applicability possesses a satisfactory range of accuracy consistent with the intended application of the model" [Schlesinger, et. al. 1979]. In several fields, this is the definition given to verification, a term used in simulation and some other areas of mathematical modelling to mean "ensuring that the model behaves as intended" [Sargent 1982]. Thus, careful attention must always be given to how the term validation (and verification) is defined and used.

Reference Type: Conference Proceedings
Author: Sargent, Robert G.
Year: 1985
Title: An Expository on Verification and Validation of Simulation Models
Conference Name: 1985 Winter Simulation Conference
Editor: D. Gantz, G. Blais, S. Solomon
Conference Location: Sacramento, CA
Pages: 15-22
Abstract: In this expository paper we give a general introduction to verification and validation of Simulation models, define the various validation techniques, and present a recommended model validation procedure.
Notes: He gives detailed procedures for verification and validation. This is a slightly expanded version of his 1982 paper.

Reference Type: Conference Proceedings
Author: Sargent, Robert G.
Year: 1990
Title: Validation of Mathematical Models
Conference Name: Symposium on Validation of Geosphere Flow and Transport Models
Conference Location: Stockholm, Sweden
Pages: 571-579
Abstract: This paper discusses the validation of computer-based mathematical models as it is performed in the fields of operations research and systems engineering. The various approaches for deciding model validity are described, a description relating model verification and validation to the model development process is given, various validation techniques are defined, a recommended validation procedure is presented, and a limited bibliography is furnished. The recommended validation procedure consists of steps that as minimum should be performed in the various phases of the model development process. This procedure is commonly used in practice; in particular for the validation of simulation models.

Reference Type: Conference Proceedings
Author: Sargent, Robert G.
Year: 1991
Title: Simulation Model Verification and Validation
Conference Name: 1991 Winter Simulation Conference
Editor: Barry L. Nelson, W. David Kelton, Gordon M. Clark
Conference Location: Phoenix, Arizona
Pages: 37-47
Abstract: This paper discusses verification and validation of simulation models. The different approaches to deciding model validity are described; how model verification and validation relate to the model development process is specified; various validation techniques are defined; conceptual model validity, model verification, operational validity are discussed; ways to document results are given; and a recommended validation procedure is presented.
Notes: The paper is very good. It is an earlier version of his 1994 and 1996 Winter Simulation Conference papers.

Reference Type: Conference Proceedings
Author: Sargent, Robert G.
Year: 1994
Title: Verification and Validation of Simulation Models
Conference Name: 1994 Winter Simulation Conference
Conference Location: Piscataway, NJ
Pages: 77-87
Abstract: This paper discusses verification and validation of simulation models. The different approaches to deciding model validity are described; how model verification and validation relate to the model development process is specified; various validation techniques are defined; conceptual model validity, model verification, operational validity, and data validity are discussed; ways to document results are given; and a recommended procedure is presented.
Notes: This paper is nearly identical to his 1996 Winter Simulation Conference paper.

Reference Type: Conference Proceedings
Author: Sargent, Robert G.
Year: 1996
Title: Verifying and Validating Simulation Models
Conference Name: 1996 Winter Simulation Conference
Editor: J. M. Charnes, D. J. Morrice, D. T. Brunner, and J. J. Swain
Conference Location: Coronado, California
Pages: 55-64
Abstract: This paper discusses verification and validation of simulation models. The different approaches to deciding model validity are presented; how model verification and validation relate to the model development process are discussed; various validation techniques are defined; conceptual model validity, model verification, operational validity, and data validity are described; ways to document results are given; and a recommended procedure is presented.

Reference Type: Conference Proceedings
Author: Sargent, Robert G.
Year: 1996
Title: Some Subjective Validation Methods Using Graphical Displays of Data
Conference Name: 1996 Winter Simulation Conference
Editor: John M. Charnes, Douglas J. Morrice, Daniel T. Brunner, James J. Swain
Conference Location: Coronado, California
Pages: 345-351
Abstract: Subjective methods for operational validity are presented that use graphical displays of histograms, box plots, and behavior graphs. These methods allow the data to be correlated, have any statistical distribution, and be limited in the number of observations. Model data are used for the reference distribution (instead of a theoretical distribution such as the t or F) and for reference to compare the system data against. These methods are very general and can be used in validating different types of models.

Reference Type: Journal Article
Author: Saunders, Carol
Year: 1985
Title: Model Validation: The Missing Process
Journal: Journal of Systems Management
Volume: 36
Issue: 8
Pages: 26-29
Abstract: The purpose of this article is to outline various approaches that may be employed in model validation and to consider steps that may be taken in order to encourage the use of this often-ignored process. There is admittedly no single set of procedures to validate models. The approaches outlined in this article, however, address three distinct and essential components of the validation process: 1) the assumptions and objectives of the model, 2) the data required for using the model, and 3) the software that manipulates the data. In most situations it would not be appropriate for the model validator to apply all of the approaches outlined in this article. Selection of approaches should be based upon costs and relative benefits, the redundancy existing between different actions and the applicability of each action to the model being validated.
Notes: Has some good ideas about model validation, but most of them are directed toward economic modeling. The ideas are also somewhat dated now.

Reference Type: Book Section
Author: Scholten, H.; van der Tol, M. W. M.
Year: 1994
Title: Towards a Metrics for Simulation Model Validation
Book Title: Predictability and Nonlinear Modelling in Natural Sciences and Economics
Editor: Grasman, J.; van Straten, G.
Publisher: Kluwer Academic
City: Boston
Pages: 398-410
Abstract: A large group of nonlinear dynamic simulation models can be seen as intermediates between hard (physical) and soft (management science) models, because they are based on insufficient or not generally accepted theories and hypotheses. This type of model (ecological, environmental, and economic) is characterized by highly uncertain outcomes, due to an uncertain, unidentifiable model structure, not well known model parameters and uncertain model inputs. Most validation techniques offer merely a terminology and a procedural validation approach without any metrics. Let S be a part of reality, which satisfies the constraints of a relevant experimental frame (specification of time, location, experimental conditions and relevant state variables). S can only be known by making observations of the real system. Any simulation model of the real system S has to be based on the available theoretical and other a priori knowledge. Each source of uncertainty will influence the model outcomes. Let O be the set of observations and M the set of model results, both within the same experimental frame, and both including uncertainty ranges, then validation tests for the fit between O and S. In the terminology of Popper most models of this class are invalid (no perfect match of O and S) and have to be rejected. This paper suggests to test for the usefulness

of a model in terms of model adequacy (which part of the system can be adequately simulated) and model reliability (which part of the model outcome matches system behavior). The test on model usefulness instead of model validity provides a metric which helps to determine the scope of the model and increases its acceptability. The method is illustrated with examples.
Notes: Gives some good ideas how to measure validation.

Reference Type: Journal Article
Author: Schreiber, F.; Keller, H. B.
Year: 1983
Title: Driven Cavity Flows by Efficient Numerical Techniques
Journal: Journal of Computational Physics
Volume: 49
Issue: 2
Pages: 310-333
Abstract: Efficient and reliable numerical techniques of high-order accuracy are presented for solving problems of steady viscous incompressible flow in the plane, and are used to obtain accurate solutions for the driven cavity. A solution is obtained at Reynolds number 10,000 on a 180 x 180 grid. The numerical methods combine an efficient linear system solver, an adaptive Newton-like method for nonlinear systems, and a continuation procedure for following a branch of solutions over a range of Reynolds numbers.
Notes: Good paper for CFD verification.

Reference Type: Magazine Article
Author: Scott, William B.
Year: 1998
Title: Better Modeling Will Alter Culture of Flight Testing
Magazine: Aviation Week & Space Technology
Pages: 84-86
Date: March 23, 1998
Abstract: Over the next decade, budget pressures and a growing dependence on modeling and simulation will alter the philosophy and methods of light testing military aircraft and weapons. The development and operational test communities are being asked to really work on altering our test philosophy, from (focusing on) specifications, to verifying a (computer) model. “That's a big change in our thrust," Engle said. "Our job now is to verify engineering models, and we're reshaping Edwards to do that".
Notes: The article has some good comments by military commanders on the need for validation in modeling and simulation.

Reference Type: Report
Author: Settles, G. S.; Dodson, L. J.
Year: 1991
Title: Hypersonic Shock/Boundary-Layer Interaction Database
Institution: NASA
Date: April 1991
Report Number: Contractor Rept. 177577
Abstract: In choosing the specific subject areas for this hypersonic database collection and

assessment effort, some caution was exercised in favor of a few critical issues directly relevant to turbulence modeling. Our purpose in this effort is to define a database for the specific goal of the advancement of modern turbulence models, not to conduct a broadbased survey of all previous work in the field of hypersonics.
Notes: Good compilation of validation data for shock/boundary-layer interaction.

Reference Type: Report
Author: Settles, G. S.; Dodson, L. J.
Year: 1993
Title: Hypersonic Turbulent Boundary-Layer and Free Shear Layer Database
Institution: NASA
Date: April 1993
Report Number: Contractor Rept. 177610
Abstract: A critical assessment and compilation of data are presented on attached hypersonic turbulent boundary layers in pressure gradients and compressible turbulent mixing layers. Extensive searches were conducted to identify candidate experiments, which were subjected to a rigorous set of acceptance criteria. Accepted datasets are both tabulated and provided in machine-readable form. The purpose of this database effort is to make existing high-quality data available in detailed form for the turbulence-modeling and computational fluid dynamics communities. While significant recent data were found on the subject of compressible turbulent mixing, the available boundary-layer/pressure-gradient experiments are all older ones of which no acceptable data were found at hypersonic Mach numbers.
Notes: Good compilation of validation data for attached and free shear layers.

Reference Type: Book
Author: Shannon, Robert E.
Year: 1975
Title: Systems Simulation: The Art and Science
Publisher: Prentice-Hall, Inc.
Abstract: Chapter 1 Fundamentals of Modeling
Chapter 2 Systems Investigation
Chapter 3 Model Translation
Chapter 4 Design of Computer Simulation Experiments
Chapter 5 Tactical Planning
Chapter 6 Validation and Analysis
Chapter 7 Management Aspects
Notes: Mainly deals with general issues in modeling and simulation.

Reference Type: Journal Article
Author: Sheng, G.; Elzas, M. S.; Oren, T. I.; Cronhjort, B. T.
Year: 1993
Title: Model Validation: A Systemic and Systematic Approach
Journal: Reliability Engineering and System Safety
Volume: 42
Pages: 247-259

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Abstract: The term 'validation' is used ubiquitously in association with the modelling activities of numerous disciplines including social, political, natural, physical sciences, and engineering. There is however, a wide range of definitions which give rise to very different interpretations of what activities the process involves. Analyses of results from the present large international effort in modelling radioactive waste disposal systems illustrate the urgent need to develop a common approach to model validation. Some possible explanations are offered to account for the present state of affairs. We believe that a rigorous approach to validation must necessarily be based on a thorough understanding and application of the theory of simulation and modeling. The methodology developed treats model validation and code verification in a systemic and systematic fashion. In fact, this approach may be regarded as a comprehensive framework to assess the adequacy of any simulation study.
Notes: This is one of the best descriptions of verification and validation I have read. It summarizes previous work and suggests a methodology for validation.

Reference Type: Journal Article
Author: Shih, T. M.; Tan, C. H.; Hwang, B. C.
Year: 1989
Title: Effects of Grid Staggering on Numerical Schemes
Journal: International Journal for Numerical Methods in Fluids
Volume: 9
Pages: 193-212
Abstract: Nine finite difference schemes using primitive variables on various grid arrangements were systematically tested on a benchmark problem of two-dimensional incompressible Navier-Stokes flows. The chosen problem is similar to the classical lid-driven cavity flow, but has a known exact solution. Also, it offers the reader an opportunity to thoroughly evaluate accuracies of various conceptual grid arrangements.
Compared to the exact solution, the non-staggered grid scheme with higher-order accuracy was found to yield an accuracy significantly better than others. In terms of overall performance, the so-called 4/1 staggered grid scheme proved to be the best. The simplicity of this scheme is the primary benefit. Furthermore, the scheme can be changed into a non-staggered grid if the pressure is replaced by the pressure gradient as a field variable.
Finally, the conventional staggered grid scheme developed by Harlow and Welch also yields relatively high accuracy and demonstrates satisfactory overall performance.
Notes: Includes manufactured solutions for CFD verification.

Reference Type: Conference Proceedings
Author: Shimazaki, K.; Himeno, Y.; Baba, N.
Year: 1993
Title: Quantification of Uncertainty in Computational Fluid Dynamics
Conference Name: Fluids Engineering Conference
Editor: Celik, I.; Chen, C. J.; Roache, P. J.; Scheuerer, G.
Publisher: American Society of Mechanical Engineers
Conference Location: Washington, DC
Volume: FED-Vol.-158
Pages: 19-28

Abstract: CFD Validation has become a topic of special importance. The basic idea of the present study is how a certain CFD code can be validated to some clearly defined degree of accuracy. A procedure for obtaining numerical errors in CFD is proposed and applied to an unsteady incompressible Navier-Stokes solution using a finite-volume method. An example for the viscous flow around a sinusoidally oscillating circular cylinder is presented to demonstrate typical numerical errors due to local truncation errors, their propagation in time and space, and errors due to incompleteness of iteration procedure.

Reference Type: Conference Proceedings
Author: Sindir, M. M.; Barson, S. L.; Chan, D. C.; Lin, W. H.
Year: 1996
Title: On the Development and Demonstration of a Code Validation Process for Industrial Applications
Conference Name: 27th AIAA Fluid Dynamics Conf.
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: New Orleans, LA
Volume: AIAA Paper No. 96-2032
Abstract: As advanced computational techniques are integrated into industrial design, analysis, and manufacturing practices, the need for a consistent, rational, and affordable code validation procedure becomes more critical. This need is especially pronounced for computational fluid dynamics (CFD), which, because of its unique ability to function both as a "numerical laboratory" as well as a predictive science, is rapidly becoming a key engineering tool. An earlier paper defined a four phase code validation procedure and related the use of CFD directly to the engineering design cycle. This paper updates that process and demonstrates its use in the development of a computational aeroacoustic analysis system. Emphasis here is on providing the operational details of the process rather than discussing in depth the error assessment techniques that are used within the process. Error assessment techniques are the topic of a subsequent paper.
Notes: The first reference I know of clearly suggesting a hierarchy of complex engineering systems for use in the validation process.

Reference Type: Conference Proceedings
Author: Sindir, M. M.; Lynch, E. D.
Year: 1997
Title: Overview of the State-of-Practice of Computational Fluid Dynamics in Advanced Propulsion System Design
Conference Name: 28th AIAA Fluid Dynamics Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Snowmass, CO
Volume: AIAA Paper No. 97-2124
Abstract: In the design of advanced propulsion systems, computational modeling plays a major role in defining the required performance over the flight envelope and testing the sensitivity of the design to the various modes of operation (e.g. rocket, ramjet, scramjet). Computational modeling techniques primarily computational fluid dynamics (CFD), together with select ground and flight testing, are expected to be the engineering tools of choice in the new Air

Force and NASA space propulsion programs. This places a premium on the development of the next generation computational tools that can be used effectively in a design environment by nonspecialists. Experience gained from use of the current tools is essential to the successful development of the new tools.
Notes: This is a very good reference for the hierarchy of complexity in the validation process.

Reference Type: Conference Proceedings
Author: Singhal, Ashok K.
Year: 1992
Title: Validation of CFD Codes and Assessment of CFD Simulations
Conference Name: Fourth International Symposium of Transport Phenomena and Dynamics of Rotating Machinery
Conference Location: Honolulu, Hawaii
Pages: 155-169
Abstract: In recent years, there has been a significant proliferation of CFD codes. It is encouraging from the point of view that CFD is finally beginning to get accepted in the industry. However, it is also frightening to see:
1. Continued overclaims by the code developers;
2. Significant confusion in the user community; and
3. Resulting wastage of CFD applications effort.
This paper focuses on the discussion of two aspects of CFD technology: validation of CFD codes and assessment of the accuracy and usefulness of CFD solutions. First, the necessary steps of a systematic validation process are discussed. Several examples are used to point out some of the common temptations and resulting pitfalls of shortcuts in validation effort. These examples highlight the necessity of additional care in the flow simulations with general curvilinear coordinates, often referred to as body fitted coordinates.
Notes: Has good procedures for CFD verification and validation

Reference Type: Conference Proceedings
Author: Singhal, Ashok K.
Year: 1998
Title: Key Elements of Verification and Validation of CFD Software
Conference Name: 29th AIAA Fluid Dynamics Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Albuquerque, NM
Volume: AIAA 98-2639
Pages: 7
Abstract: The verification and validation of CFD software is of utmost importance for the reliability and hence for the success of CFD technology in industry. This paper discusses the relative importance, key elements, and some examples of:
- Verification of numerical models and computer software,
- Validation of solutions against benchmark data; and
- Calibration of the models and analysis process.
Out of these, the main emphasis is placed on verification. This is in light of the growing generality and complexity of CFD software (in response to continuously increasing expectations in industry). Finally, three key success factors for effective utilization of CFD

technology are pointed out. These are 1) Verifications and Validation of software; 2) Skills of the Users; and 3) Vision, and commitment of the manager(s).
Notes: Very good discussion of verification and validation procedures for CFD codes.

Reference Type: Journal Article
Author: Smith, Jeffrey H.
Year: 1993
Title: Modeling Muddles: Validation Beyond the Numbers
Journal: European Journal of Operational Research
Volume: 66
Pages: 235-249
Abstract: A nonnumerical methodology for estimating the validity of complex models is presented. The validity of such models was estimated qualitatively by identifying the arguments used by the interested parties associated with the model. The patterns of reasoning about the foundations of the model were identified through an analysis of the arguments defending and denying the validity of the model. The approach is illustrated by using the expected utility (EU) model as an example. The analysis revealed contrasting sets of pro-EU and con-EU model arguments. A fundamental difference in the forms of arguments was observed: The pro-EU model used broad arguments covering a variety of issues (top-down) and the con-EU model used specific empirical results to question the fundamental grounding of EU model theory (bottom-up). The approach holds promise for large complex models that are difficult, if not impossible, to validate quantitatively.
Notes: He suggest a non-quantitative method for model validation. This seems it might work for conceptual model validation.

Reference Type: Book
Author: Smith, S.; Kandel, A.
Year: 1993
Title: Verification and Validation of Rule-Based Expert Systems
Publisher: CRC Press
City: Boca Raton, FL
Notes: Good modern reference for software V&V procedures

Reference Type: Book
Author: Soong, T. T.
Year: 1991
Title: Probabilistic Modeling and Analysis in Science and Engineering
Publisher: John Wiley & Sons
City: New York
Edition: 1st
Abstract: I. Introduction
II. Basic Probability Concepts
III. Random Variables and Probability Distributions
IV. Expectations and Moments
V. Functions of Random Variables

VI. Some Important Discrete Distributions
VII. Some Important Continuous Distributions
VIII. Observed Data and Graphical Representation
IX. Parameter Estimation
X. Model Verification
XI. Linear Models and Linear Regression
Notes: Good book for probability and statistics, but very little connection to examples in engineering and science.

Reference Type: Conference Proceedings
Author: Springer, A. M.
Year: 1998
Title: Comparison of the Aerodynamic Characteristics of Similar Models in two Different Size Wind Tunnels at Transonic Speeds
Conference Name: 20th AIAA Advanced Measurement and Ground Testing Technology Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Albuquerque, NM
Volume: AIAA 98-2875
Pages: 7
Abstract: The aerodynamic characteristics of two similar models of a lifting body configuration were run in two transonic wind tunnels - one a 16-foot and the other a 14-inch are compared. The 16-foot test used a 2-percent model while the 14-inch test used a 0.7-percent scale model. The wind tunnel model configurations varied only in vertical tail size and the 2-percent model had an aft sting shroud. The results from these two tests compare the effect of tunnel size, Reynolds number, and dynamic pressure on the longitudinal aerodynamic characteristics of the vehicle. The data accuracy and uncertainty are also presented. It was concluded from these tests that the data resultant from a small wind tunnel compare very well to that of a much larger wind tunnel in relation to total vehicle aerodynamic characteristics.
Notes: Good paper for estimating bias error in validation data for CFD

Reference Type: Journal Article
Author: Srinivasan, R.
Year: 1995
Title: Accurate Solutions for Steady Plane Flow in the Driven Cavity. I. Stokes Flow
Journal: Zeitschrift fur Angewandte Mathematik und Physik
Volume: 46
Issue: 4
Pages: 524-545
Abstract: The incompressible plane flow generated by uniform translation of the upper wall in a rectangular cavity has received considerable attention in the literature because of the complex flow characteristics exhibited in a relatively simple geometry. This problem has been previously studied numerically using various techniques, including finite-difference, multigrid, spectral, finite element and integral equation methods. For the Stokes flow problem (zero Reynolds number) analytical solutions based on eigenfunction expansions have been derived

by Joseph and Sturges and Shankar. The driven cavity problem has also been of great interest as a test problem for evaluating numerical procedures for solving the Navier-Stokes equations.
Notes: Good paper for CFD verification.

Reference Type: Book Section
Author: Stager, Paul
Year: 1993
Title: Validation in Complex Systems: Behavioral Issues
Book Title: Verification and Validation of Complex Systems: Human Factors Issues
Editor: Wise, John A.; Hopkin, V. David; Stager, Paul
Publisher: Springer-Verlag
City: Toronto, Ontario
Pages: 99-114
Abstract: The intent of this paper is to review some of the behavior and methodological issues for validation in complex human-machine systems. In an earlier discussion of automation issues in complex operational systems (Wise, Hopkin, & Smith, 1991) system performance was seen to depend both on the functionality inherent in the engineering design and on the interactive processes between the operators and the system, including the operators' perceptions of their roles in the automated system. The very interactive nature of behavior in operational systems inevitably leads to the consideration of methodological requirements for system validation. Contemporary human engineering design (and ultimately system validation) is challenged by the requirement to accommodate and to predict the variance in human behavior in complex human-machine systems, in spite of the practical constraints placed on studies of operator behavior.

Reference Type: Conference Proceedings
Author: Summa, J. M.; Barton, J. M.
Year: 1998
Title: CFD Verification and Validation in Commercial Design and Analysis
Conference Name: 29th AIAA Fluid Dynamics Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Albuquerque, NM
Volume: AIAA 98-2640
Pages: 12
Abstract: The processes of verification and validation are discussed and illustrated in the business context of combined software sales, design services, and customer support for aircraft certification. The processes are shown to be ongoing efforts, rather than once-for-all-times, and are highlighted with application to business jets and commercial transports. Particular needs are addressed in the case of complete aircraft configurations.

Reference Type: Journal Article
Author: Terrill, R. M.; Colgan, T.
Year: 1991
Title: Some Simple Analytic Solutions of the Navier-Stokes Equations
Journal: International Journal of Engineering Science

Volume: 29
Issue: 1
Pages: 55-68
Abstract: Some families of axisymmetric solutions are obtained for flows through pipes with circular cross-sections that vary in the axial direction and with appropriate mass transfer rates at the wall. Their simple analytic forms make particular cases suitable as examples for students. A feature of the paper is that it can be seen that by adding two different families of solutions of the non-linear differential equations a completely different family of boundaries is produced.
Notes: Good reference for analytical solutions used in code verification

Reference Type: Personal Communication
Author: Trucano, Timothy
Year: 1996
Title: On the Path to Prediction: Verification and Validation
Date: October 31, 1996
Abstract: Outline of the Presentation:
1. What is "verification" and "validation"
2. Systems and Uncertainty
3. The need for statistical inference
4. Next steps
Notes: Presentation discussing the relationship of verification and validation and uncertainty estimation.

Reference Type: Conference Proceedings
Author: Tsang, Chin-Fu
Year: 1989
Title: A Broad View of Model Validation
Conference Name: Proceedings of the Symposium on Safety Assessment of Radioactive Waste Repositories
Publisher: OECD, Paris, France
Conference Location: Paris, France
Pages: 707-716
Abstract: The safety assessment of a nuclear waste repository requires the use of models. Such models need to be validated to ensure, as much as possible, that they are a good representation of the actual processes occurring in the real system. In this paper we attempt to take a broad view by reviewing step by step the modeling process and bringing out the need to validating every step of this process. Thus model validation includes not only comparison of modeling results with data from selected experiments, but also evaluation of procedures for the construction of conceptual models and calculational models as well as methodologies for studying data and parameter correlation. The need for advancing basic scientific knowledge in related fields, for multiple assessment groups, and for presenting our modeling efforts in open literature to public scrutiny is also emphasized.

Reference Type: Journal Article
Author: Van De Vooren, A. I.; Dijkstra, D.

Year: 1970
Title: The Navier-Stokes Solution for Laminar Flow Past a Semi-Infinite Flat Plate
Journal: Journal of Engineering Mathematics
Volume: 4
Issue: 1
Pages: 9-27
Abstract: A numerical solution joining Carrier and Lin's solution near the leading edge to the boundary layer solution at large distance of the leading edge is presented. The solution is valid for any Reynolds number. Results are given for the skin friction, the integrated skin friction, the displacement thickness, the pressure along the plate and the velocity ahead of the plate. The asymptotic value of the integrated skin friction agrees very well with the exact value. The displacement thickness is already different from zero for small distances ahead of the plate.
Notes: Good paper for CFD verification.

Reference Type: Conference Proceedings
Author: Van Wie, D. M.; Rice, T.
Year: 1996
Title: Quantification of Data Uncertainties and Validation of CFD Results in the Development of Hypersonic Airbreathing Engines
Conference Name: 27th AIAA Fluid Dynamics Conference
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: New Orleans, LA
Volume: AIAA 96-2028
Pages: 12
Abstract: The developing process for hypersonic airbreathing engines is evolving, and the validation of computational and experimental techniques plays an increasingly vital role as a greater understanding of the physical processes is realized. A series of examples is provided to illustrate some of the important aspects of this validation. Sample engine calculations are used to estimate the required accuracies needed for the validation process. Techniques for the measurement of scramjet performance are considered to illustrate the difficulties encountered in collecting data for the validation process. The need to carefully assess measurement uncertainties and propagate these uncertainties through analysis procedures is discussed. Finally, the need to understand trends and sensitivities is described.

Reference Type: Conference Proceedings
Author: Veazey, D. T.; Hopf, J. C.
Year: 1998
Title: Comparison of Aerodynamic Data Obtained in the Arnold Engineering Development Center Wind Tunnels 4T and 16T
Conference Name: 20th AIAA Advanced Measurement and Ground Testing Technology
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Albuquerque, NM
Volume: AIAA 98-2874
Pages: 18
Abstract: Arnold Engineering Development Center (AEDC) wind tunnels 4T and 16T have evolved into productive wind tunnel test facilities. Both tunnels are noted for achieving

outstanding flow quality and producing high quality data. Tunnel-to-tunnel comparisons of aerodynamic, store separation, and tunnel calibration data will be presented to reinforce this tenet.
The data are presented at subsonic, transonic, and low supersonic Mach numbers, and have been obtained over a span of several years in the AEDC test facilities. The test articles include a 1/5-scale model of a typical missile used to acquire aerodynamic static stability data and a 1/15-scale model of a slender body missile shape employed for store separation testing. The test conditions evaluated include Mach numbers from 0.4 to 1.6, model angles of attack from -27 to 27 deg, and Reynolds numbers from 1.1 to 2.5 million/ft.
Notes: Good for estimating bias errors in validation data in CFD.

Reference Type: Conference Proceedings
Author: Verhoff, A.
Year: 1998
Title: Complementing Numerical Simulation Methods with Classical Analytical Techniques
Conference Name: 2nd AIAA Theoretical Fluid Mechanics Meeting
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Albuquerque, NM
Volume: AIAA 98-2486
Pages: 22
Abstract: New aerospace vehicle designs must have greater performance and versatility at affordable cost. This requires multi-disciplinary analysis and optimization which in turn requires more accurate and efficient numerical simulation tools. The need for greater accuracy and efficiency of Computational Fluid Dynamics (CFD) tools is further amplified by the industry trend toward distributed computing and away from supercomputers. Complementary analytical methods coupled with traditional CFD approaches offer the means for increased simulation capability by incorporating more essential physics into solution algorithms and reducing reliance on grid density for achieving accuracy. This paper describes activities directed at improving affordability of CFD tools with complementary analytical techniques. Results have proven very successful. Several examples of ongoing work are discussed, including analytical-based aerodynamic analysis and design optimization methods and improved far-field boundary conditions for CFD codes. These examples illustrate the synergism that can be realized from coupling analytical and numerical methods.
Notes: Has good solutions for verification of CFD solutions.

Reference Type: Conference Proceedings
Author: Verhoff, A.; Cary, A.
Year: 1998
Title: Analytical Euler Solutions for 2D Flows with Corners using Asymptotic Methods
Conference Name: 2nd AIAA Theoretical Fluid Mechanics Meeting
Publisher: American Institute of Aeronautics and Astronautics
Conference Location: Albuquerque, NM
Volume: AIAA 98-2687
Pages: 10
Abstract: A newly-developed procedure for obtaining analytical asymptotic solutions of the 2D

steady-state Euler equations is applied to compressible flows with geometric corners. The equations are written in natural streamline coordinates with mass flux and flow angle as dependent variables. Higher-order compressibility and rotationality effects appear as non-homogeneous forcing terms. This new solution approach does not require a Green's function for the forcing terms and thus general applicability to Poisson equations and non-homogeneous Cauchy-Riemann systems. It therefore has application to many other disciplines (e.g., heat transfer) besides fluid dynamics. Application of the new approach to flow problems with geometric corners reveals the typical singularity compounding at higher order. The analytical nature of the solutions guides implementation of coordinate straining to control the phenomenon. Closed-form asymptotic solutions with coordinate straining are likewise straightforward. Solutions of this type can serve as a guide for development of improved surface boundary conditions near geometric corners for CFD Euler calculations.
Notes: Good for high accuracy solutions for CFD verification

Reference Type: Journal Article
Author: Walker, M. A.; Oberkampf, W. L.
Year: 1992
Title: Joint Computational/Experimental Aerodynamics Research on a Hypersonic Vehicle: Part 2, Computational Results
Journal: AIAA Journal
Volume: 30
Issue: 8
Pages: 2010-2016
Abstract: Parabolized and iterative Navier-Stokes codes are used to predict flowfield solutions around a hypersonic vehicle. Aerodynamic force and moment predictions from the codes are compared with experimental data from the Sandia National Laboratories Mach 8 wind tunnel. The comparisons are made on a spherically blunted cone with a slice parallel to the body axis. On the slice portion of the vehicle, a flap can be attached so that deflection angles of 10, 20, and 30 deg can be obtained. The Sandia parabolized Navier-Stokes code is used to generate solutions for the sliced vehicle with no flap. For the vehicle with a flap, axially separated flow occurs, and a time iterative Navier-Stokes code is used to provide comparisons with the data. Aerodynamic force and moment comparisons are made for laminar flow, and an ideal gas is assumed in the calculations. A detailed study of grid convergence is presented to determine the accuracy of the numerical solutions. Predictions obtained from the codes show very good agreement with the experimental data for force and moment coefficients, except for large flap deflections.
Notes: Good 3-D solutions for CFD verification and also has comparisons with validation quality data.

Reference Type: Report
Author: Wallace, Dolores R.; Ippolito, Laura M.; Cuthill, Barbara B.
Year: 1996
Title: Reference Information for the Software Verification and Validation Process
Date: April 1996
Report Number: 500-234

Abstract: Computing systems may be employed in the health care environment in efforts to increase reliability of care and reduce costs. Software verification and validation (V&V) is an aid in determining that the software requirements are implemented correctly and completely and are traceable to system requirements. It helps to ensure that those system functions controlled by software are secure, reliable, and maintainable. Software V&V is conducted throughout the planning, development and maintenance of software systems, including knowledge-based systems, and may assist in assuring appropriate reuse of software.
Notes: Has very good description of procedures for software verification

Reference Type: Book Section
Author: Wang, C. Y.
Year: 1991
Title: Exact Solutions of the Steady-State Navier-Stokes Equations
Book Title: Annual Review of Fluid Mechanics
Editor: Lumley, J. L.; Van Dyke, M.
Publisher: Annual Reviews, Inc.
City: Palo Alto, CA
Volume: 23
Pages: 159-177
Abstract: The only comprehensive review of exact solutions of the Navier-Stokes equations is that due to Berker (1963), which expanded on the earlier works of Berker (1936) and Dryden (1932). Other sources include those of Whitham (1963) and Schlichting (1968). Since then, many new solutions have appeared, and a new review is necessary. The unsteady exact solutions were recently reviewed by Wang (1989). The present work is the complement of that source, being a review of the steady exact solutions. Because of the difficult nature of the task, in spite of a careful search, there may be works that escaped our notice. To these authors, we offer our sincere apologies.
Notes: Good paper for verification solutions for CFD.

Reference Type: Book Section
Author: Westrum, Ron
Year: 1993
Title: Cultures with Requisite Imagination
Book Title: Verification and Validation of Complex Systems: Human Factors Issues
Editor: Wise, John A.; Hopkin, V. David; Stager, Paul
Publisher: Springer-Verlag
City: Ypsilanti, MI
Pages: 401-416
Abstract: When a large system is developed, there are always, in the early stages, a great number of serious problems with it. In some organizations these serious problems are quickly noted and rapidly attacked. In others they are hidden, skirted, or only half-solved. If we call the former organizations effective and the latter ineffective, we are led to an obvious question: what distinguishes the effective from the ineffective ones? The differences in performance are apparent; we need to explore their causes. In this report, I will use engineering examples from the 19th and 20th centuries to develop a more detailed picture of the kinds of differences that

exist between those organizations likely to vet their systems successfully and those unlikely to do so.

Reference Type: Book Section
Author: Wieringa, Peter A.; Stassen, Henk G.
Year: 1993
Title: Assessment of Complexity
Book Title: Verification and Validation of Complex Systems: Human Factors Issues
Editor: Wise, John A.; Hopkin, V. David; Stager, Paul
Publisher: Springer-Verlag
City: The Netherlands
Pages: 173-180
Abstract: In his book about chaos, Gleick (1988) describes how the meteorologist E. Lorenz in 1961 found that small numerical errors in the initial conditions for his deterministic model of the weather could unfold into simulated catastrophes. A similar threat is real for automated large scale systems that contain deterministic subsystems whose behavior is described by difference equations. The appreciation that small errors in the design, measuring device, or (human) control action are also subject to the so-called Butterfly Effect induces stress upon the human supervisory task.

Reference Type: Edited Book
Editor: Wise, John A.; Hopkin, V. David; Stager, Paul
Year: 1993
Title: Verification and Validation of Complex Systems: Human Factors Issues
Publisher: Springer-Verlag Berlin
City: Berlin
Abstract: Section 1 Perspectives on Verification and Validation
Section 2 Developing Definitions and Approaches
Section 3 Complexity in a Systems Context
Section 4 Reliability, Errors, and Safety
Section 5 Operator Capabilities and Variability
Section 6 Mental Models in Operational Systems
Section 7 The Cultural Context
Section 8 Involving the Users in Verification and Validation Processes
Section 9 The Need for User Involvement
Section 10 Other Applications Contexts
Section 11 Training and Implementation
Section 12 Retrospect
Notes: Very good fundamental view of verification and validation of simulation models and control systems.

Reference Type: Book Section
Author: Wise, John A.; Wise, Mark A.
Year: 1993
Title: Basic Considerations in Verification and Validation

Y

Book Title: Verification and Validation of Complex Systems: Human Factors Issues
Editor: Wise, John A.; Hopkin, V. David; Stager, Paul
Publisher: Springer-Verlag
Pages: 87-95
Abstract: Verification and validation of systems is becoming extremely important in the process of developing the devices we use in modern life. Rapid advances in technology and software have provided the capability to develop very complex systems with highly coupled components (i.e., components that are highly interdependent). Such systems can significantly increase efficiency and allow the development and operation of systems that were previously impossible. Perrow (1984), however, argues that complex systems that are also highly-coupled are inherently unstable and are susceptible to system induced catastrophes.
As systems become more coupled, interdisciplinary issues become more critical. In coupled systems it is likely that new operational interface problems will reside in locations where disciplines (and the system components relevant to their domain) meet and interact. It is in these intellectual intersections that most new compromises and cross-discipline trade-off are made. And it will be in these intersections that new interface induced failures will emerge that will probably not be anticipated.

Reference Type: Journal Article
Author: Yoshizawa, A.
Year: 1970
Title: Laminar Viscous Flow Past a Semi-Infinite Flat Plate
Journal: Journal of the Physical Society of Japan
Volume: 28
Issue: 3
Pages: 776-779
Abstract: The laminar viscous flow past a semi-infinite flat plate set parallel to a uniform stream is studied by solving the Navier-Stokes equations numerically. The boundary-layer-and Stokes-type successive approximations give the following expansions of the local skin-friction coefficient Ct: where the constants a, b and C are to be determined, and R is the Reynolds number based on the distance measured along the flat plate from the leading edge. From the present numerical results, the constants, a, b and C are estimated as follows: a=0.374, b=0.022, C=0.3.
Notes: Good paper for CFD verification.

Reference Type: Book
Author: Zeigler, Bernard P.
Year: 1976
Title: Theory of Modelling and Simulation
Publisher: John Wiley & Sons
City: New York
Edition: 1st
Abstract: 1. The Enterprise of Modelling and its Communication
2. The Five Elements
3. Prototype Simulation and Formal Model Specification
4. Simulation of Cell-Space-Like Models

5. Simulation of Discrete and Continuous Time Models
6. Introduction of Discrete Event Models
7. Discrete Event Simulation Strategies and Models
8. Introduction of Modelling Theory
9. Hierarchy of System Specifications
10. Hierarchy of Preservation Relations
11. Framework for Modelling and Simulation
12. Valid Model Construction and Simplification
13. Approximation and Error Tolerance
14. State Identification, Validation, and Prediction
15. Structural Inference

Notes: Very good fundamentals in the theory of modelling and simulation. Reprinted in 1984 by Krieger Publishers (Lib. Congress No. 84-19443).

Reference Type: Conference Proceedings
Author: Zhang, X. D.; Trepanier, J. Y.; Camarero, R.
Year: 1997
Title: An A Posteriori Error Estimation Method Based on Error Equations
Conference Name: 13th Computational Fluid Dynamics Conference
Conference Location: Snowmass Village, CO
Publisher: American Institute of Aeronautics and Astronautics
Volume: AIAA 97-1889
Pages: 383-397
Abstract: An error equation is proposed as a way to obtain error estimation for hyperbolic systems of conservation laws. The error equation behaves as the initial equation but is driven by a source term computed from the flux jump at interfaces. The error equation is solved simultaneously with the initial equation. Comparisons with exact error distributions show that the estimated error distribution is captured very well for all variables. A quantitative agreement can be obtained if higher-order schemes are used for the error equation.
Notes: Gives a good method of error estimation for finite volume, unstructured grids. Good for verification and validation.

Reference Type: Journal Article
Author: Zingg, D. W.
Year: 1992
Title: Grid Studies for Thin-Layer Navier-Stokes Computations of Airfoil Flowfields
Journal: AIAA Journal
Volume: 30
Issue: 10
Pages: 2561-2564
Abstract: The purpose of this Note is to evaluate numerical errors for a range of flow cases and to reduce them to reasonable levels. This is accomplished through numerical solution-to-solution comparisons including grid-refinement studies and outer boundary-position studies. Error estimates are obtained using Richardson extrapolation, as in Ref. 2. In addition to providing useful guidelines for determining the levels of grid refinement and the outer

boundary position required to achieve a given level of accuracy, the grid-independent solutions obtained provide an accurate evaluation of physical-model errors. Further details of the present study are included in Ref. 3.
Notes: Good for verification solutions in CFD.

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Author: Zeigler, Bernard P.

Year: 1979
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Year: 1985
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